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AIRCRAFT AND REFUELER BONDING AND GROUNDING STUDY

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COORDINATING RESEARCH COUNCIL, INC.
219 PERIMETER CENTER PARKWAY, ATLANTA, GEORGIA 30346

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COORDINATING RESEARCH COUNCIL
INCORPORATED
219 PERIMETER CENTER PARKWAY
ATLANTA, GEORGIA USA 30346
PHONE: (404) 396-3400
FAX: (404) 39[illegible]104

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Prepared by the

CRC Bonding and Grounding Task Force

of the

CRC-Aviation Electrical Discharges Liaison Group

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CRC Aviation Fuel, Lubricant, and Equipment Research Committee

of the

Coordinating Research Council, Inc.

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EXECUTIVE SUMMARY

The 1990 Edition of NFPA 407, Standard on Aircraft Fuel Servicing, deleted the requirement for grounding during aircraft fueling and tank truck loading. This change has caused a great deal of concern in the industry since it impacts not only refueling operations, but also airport construction and maintenance.

In order to resolve the more controversial aspects of this change, the Coordinating Research Council (CRC) Electrical Discharges Liaison Group conducted a series of tests at Denver Stapleton Airport, 30 October - 8 November 1991. This test program culminated in a demonstration of a simulated aircraft refueling operation conducted with and without the use of ground wires. The demonstration was witnessed by representatives from the FAA, the airline, air cargo and aircraft fueling industries, airport design industry and the Denver Fire Department. The program did not address grounding requirements for purposes other than refueling.

For these tests, a hydrant servicer was used to generate the charge on the fuel at flow rates of 450 or 900 gpm (0.0284 or 0.0568 m^3/s). An 8,000 gal (30.3 m^3) cylindrical tank was used to simulate an aircraft fuel tank or a refueler. Measurements were made of the following quantities with the tank bonded and grounded [as per NFPA 407, 1985 Edition] and with the ground wire deleted [as per NFPA 407, 1990 Edition]:

(1) Charge density entering the tank

(2) Electrostatic field strength

(3) Electrostatic discharges in the tank

(4) Voltage on the tank

(5) Current flow in the bond wire

(6) Current flow in the ground wire

Initially, the measurements were made with the wheels of both the hydrant servicer and the tank resting on concrete as in most fueling operations. Then, to simulate a worst case scenario, i.e., a refueling operation in the desert or the arctic where there would be little or no charge relaxation through the tires, all of the wheels of the hydrant servicer and of the tank were placed on teflon pads and the measurements were repeated, with and without grounding.

The following conclusions were derived from this study:

1. When the hydrant servicer and receiving tank were properly bonded and grounded as per the 1985 Edition of NFPA 407, field strengths of several hundred kV/m were observed in the tank. In other words, bonding and grounding do not prevent the accumulation of charge in the tank. The field strength was found to decay to essentially zero within one minute after flow was stopped as the charge on the fuel relaxed. There was no voltage build up on the tank, as expected, since the tank was grounded.

2. Removal of the ground wire had no effect on:

   (a) charge generation

   (b) field strength in the receiving tank

   (c) voltage buildup on the tank during filling or

   (d) the rate at which the charge relaxes after flow is stopped,

   as long as the bond wire was in place. This conclusion was found to be valid when the tires of both the hydrant servicer (or refueler) were resting on a concrete surface, as in most refuelling operations, or were on teflon pads, which simulate a worst case scenario in which charge cannot relax through the tires.

3. No discharges were detected in any of the runs, regardless of whether or not the vehicles were bonded and/or grounded.

4. These tests demonstrated that deletion of the requirement for grounding during aircraft refueling and tank truck loading, as recommended in NFPA 407 1990 Edition, does not result in an increased electrostatic hazard as long as the bond wire is in place. The bond wire provides a path for the charges separated at the filter to recombine with the charges in the fuel tank, thereby permitting charge neutralization to occur in the absence of a ground wire.

5. Finally, no amount of bonding and grounding will eliminate the primary electrostatic hazard during refueling operations, i.e., an electrostatic discharge in the vapor space of the tank. This hazard can be eliminated only by the use of a static dissipator additive in the fuel or by providing adequate relaxation time between the filter separator and the tank. (For tank truck and refueler loading, at least 30 seconds relaxation time is generally recommended: no comparable value has been stipulated for aircraft refueling.)

AIRCRAFT AND REFUELER BONDING AND GROUNDING STUDY

BACKGROUND

The 1990 Edition of NFPA 407, Standard on Aircraft Fuel Servicing (1), deleted the requirement for grounding during aircraft fueling and tank truck loading. This change has caused a great deal of concern in the industry since it impacts not only refueling operations, but also airport construction and maintenance. Part of the controversy resulted from a misinterpretation of the change in grounding requirements in NFPA 407. Some readers felt that if grounding was not required for fueling operations, it wasn't required for any operation. Nothing could be further from the truth. NFPA 407, 1990 Edition states explicitly:

> "If ground support equipment is connected to the aircraft or if other operations are being conducted that require electrical earthing, then separate connections must be made for this purpose."

The reason for making this distinction between static grounding and electrical grounding lies in the difference in the resistance requirements for the two types of grounding, namely: a static ground may have a resistance as high as 10^6 ohms (2), whereas an electrical ground must be less than 10 ohms (3).

The controversy over bonding and grounding has been with us for some time. The 1961 Edition of NFPA 407 (4) stated that:

> "Much of the interest and controversy delaying first issuance of these recommendations for four years centered on the technical justification, if any, for static grounding (as opposed to static bonding) recommendations specified in Article 220 herein. No truly adequate test program has been conducted to establish with certainty the need for this protection up to May 1961 although efforts are continuing to secure the desired research."

On the other hand, NFPA 77, "Recommended Practice on Static Electricity" (2) has maintained over the years that bonding only was required during aircraft refueling and stated further that:

> "4-6.1.6 Some regulations require, in addition to the bonding required in this section, that the aircraft and fueling system be connected by wires to ground. However, in many locations grounds are not available and evidence does not indicate that grounding is necessary for protection against static ignition. (See NFPA 407, Aircraft Fuel Servicing.)"

In order to resolve the more controversial aspects of the change in grounding requirements in the 1990 Edition of NFPA 407, the Coordinating Research Council (CRC) Electrical Discharges Liaison Group conducted a series of tests at Denver Stapleton Airport, 30 October - 8 November 1991. (Membership of the CRC Bonding and Grounding Task Force and the participants in the Denver Test Program are listed in Appendix A). This test program culminated in a demonstration of a simulated aircraft refueling operation conducted with and without the use of ground wires. The demonstration was witnessed by representatives from the FAA, the airline, air cargo and aircraft fueling industries, airport design industry and the Denver Fire Department. The program did not address grounding requirements for purposes other than refueling.

The results of this study and a description of the bonding and grounding demonstration are the subject of this report.

OBJECTIVE

The objective of this program was to determine if deletion of the requirement for grounding during aircraft refueling and tank truck loading will result in an increased electrostatic hazard during these operations.

APPROACH

Using a 8,000 gal (30.3 m^3) cylindrical tank to simulate an aircraft fuel tank or a refueler, measurements were made of the following quantities with the tank bonded and grounded [as per NFPA 407, 1985 Edition (5)] and with the ground wire deleted [as per NFPA 407, 1990 Edition (1)]:

(1) Charge density entering the tank

(2) Electrostatic field strength

(3) Electrostatic discharges in the tank

(4) Voltage on the tank

(5) Current flow in the bond wire

(6) Current flow in the ground wire

Initially, the measurements were made with the wheels of both the hydrant servicer and the tank resting on concrete as in most fueling operations. Then, to simulate a worst case scenario, i.e., a refueling operation in the desert or the arctic where there would be little or no charge relaxation through the tires, all of the wheels of the hydrant servicer and of the tank were placed on teflon pads and the measurements were repeated, with and without grounding. The complete test matrix is given in Table 1.

In addition, since the ability of aircraft tires to dissipate static electricity is also of interest, the resistance of the tires on several types of commercial aircraft were determined on both concrete and asphalt surfaces.

APPARATUS

The experimental set-up is shown schematically in Fig. 1 and pictorially in Fig. 2.

An 8,000 gallon ($30.3\ m^3$) cylindrical tank [diameter = 8 ft (2.4 m) and length = 20 ft (6.1 m)] was used to simulate an aircraft tank or tank truck. The tank was positioned on a low boy trailer. The front trailer supports ('landing gear') and the front dual trailer wheels of the trailer rested on teflon pads [2 ft x 2 ft x 1/2 in. (0.61 x 0.61 x 0.013 m)] - see Figs. 3 and 4. The rear wheels of the trailer rested on concrete for Runs 1 to 15B to simulate normal loading conditions and on teflon pads for Runs 16a to 23 for the worst case scenario. (Note - It was not possible to position the landing gear and front trailer wheels on concrete due to the arrangement of the test stand. Without the teflon pads, these wheels would have been resting on asphalt giving a mixed grounding path from the tank. With these wheels on teflon pads, the rear wheels, on concrete, provided a grounding path for the tank for Runs 1 - 15b). The tank was connected to the fueling yoke via an isolation flange gasket kit which provided a resistance of 13MΩ. The outlet hose and the nitrogen purge lines were disconnected during each run to eliminate extraneous grounding paths.

Jet A fuel was pumped from the storage tank through a hydrant servicer equipped with CDF Fuel Monitors, which generated the static charge, and into the receiving tank. Two AO Smith Charge Density Meters were used to measure the charge on the incoming fuel. For Test Series I - IV, i.e., Runs 1 - 15b, the wheels of the hydrant servicer rested on concrete as in a normal fueling operation and the servicer was connected to the pit valve via a Type C conductive hose. The resistance to ground of the hydrant servicer in this configuration, i.e., without the ground wire connected to the grounding point on the rack and with no hose connections to the tank, was 19 kΩ. The ground wire was connected to the loading rack for Runs 1-8, but not for Runs 9-14.

An attempt was made to use a Dart Refueler in order to obtain comparable fuel charging data for a refueler. Despite the fact that the Dart was equipped with new coalescer elements (Velcon 83) and the same fuel and high flow rates were used, no fuel charging was obtained. This failure was attributed to the known low charging characteristics of the Velcon elements and to the additional relaxation time for the Dart Refueler (6 seconds vs. 2 seconds for the hydrant servicer).

Since sufficient fuel charging could not be obtained with the Dart Refueler, the hydrant servicer was modified to simulate a refueler for Test Series III - V, i.e., Runs 15a - 22. This modification consisted in the installation of an isolation flange gasket kit at the hydrant pit valve and placing the loading hose on a teflon pad to eliminate this path to ground. The resistance of the hydrant servicer to ground in this configuration, i.e., with the loading hose electrically isolated and with the wheels of the servic-

er on concrete and no hose connection to the receiving tank was 300 kΩ, which was essentially the resistance of the tires to ground. This was the arrangement for Runs 15a and 15b except that the hose was connected to the receiving tank.

For Test Series V and the Demonstrations (Runs 16a - 23), the wheels of the hydrant servicer were placed on teflon pads to simulate a worst case scenario, i.e., a refueling operation in the desert or the arctic where there would be little or no charge relaxation through the tires. The resistance of the hydrant servicer to ground in this configuration, i.e., with the isolation flange gasket kit installed at the pit valve, the loading hose and wheels of the servicer on teflon pads and no hose connections to the receiving tank, was 100 MΩ for Runs 16a - 18. The isolation flange was then refitted and a resistance of 200 MΩ was attained for Runs 19-23. The resistance of the receiving tank to ground when all of the tires and the landing gear were resting on Teflon pads and with no connections to the hydrant servicer was 2000 MΩ.

A Keithley 617 Programmable Electrometer was used to measure the current in the bonding wire and in the ground cable during certain runs.

The electrostatic field strength in the receiving tank was measured by a specially designed, pneumatically-driven field meter provided by Mobil Research and Development Corporation. The calibration curve for this field meter is shown in Fig. 5. The output of the field meter was fed into a strip chart recorder.

A Panasonic Charge Coupler Device video camera (Model CL-702, with a WV-LA lens) was placed in the center hatch, along side the field meter, to detect discharges. The sensitivity of this video camera was checked by placing the camera in a dark room at a distance of 6 ft (2 m) from a piezoelectric, bunsen burner spark igniter which produces a 3/16 in. (0.476 cm) spark discharge. The discharge was clearly visible on the video display.

This video camera provided coverage over a 10 ft. (3.0 m) diameter area in the center of the tank. For Runs 10 to 23, a second video camera was installed in the forward hatch to provide additional coverage.

The leads from all of the instrumentation were suspended in such a manner as to preclude contact with the tank.

A Sensitive Research Electrostatic Voltmeter (Range 0-125V) was used to measure the voltage on the receiving tank for all runs except Run 18 when the tank was resting on teflon and both the bond wire and the ground wire were disconnected. For this run, a Sensitive Research Electrostatic Voltmeter with a range of 0-5000 V was used.

EXPERIMENTAL PROCEDURE

After inerting with nitrogen, the tank was filled slowly to the 1000 gal (0.38 m^3) mark to prevent splashing the fuel (the tank was not equipped with a diffuser). The tank was then filled at the desired flow rate [nominally 450 or 900 gpm (0.0284 or 0.0568 m^3/s)] until the fuel level reached the 6500 gallon (24.6 m^3) mark whereupon flow was stopped. The fuel flow rate, the charge density on the incoming fuel, the field strength in the tank, the voltage on the tank and the output of video discharge detectors were recorded during each run. Following each run, a sample of fuel was taken for measurement of electrical conductivity using an Emcee Electronics Fuel Conductivity Meter.

Aircraft tire resistance measurements were made using a Biddle Instruments Megger. The high voltage lead of the megger was connected to a convenient grounding point on the aircraft and the ground lead to the grounding point nearest to the aircraft.

RESULTS

Series 1 - Tank and Servicer Bonded and Grounded

During the first test series, Runs 1 - 8, the hydrant servicer and tank were bonded and grounded as per NFPA 407, 1985 Edition (5). The wheels of the servicer and the rear four wheels of the tank trailer were resting on concrete. The other 4 wheels of the tank trailer and the front trailer supports were resting on teflon pads as shown in Figs. 3 and 4. The resistance of the tank trailer to ground before the hoses were connected was 75 kΩ and the resistance of the hydrant servicer to ground with the conductive hose (Type C) connected to the hydrant pit valve and with no other connection to the tank was 19 kΩ. The resistance to ground of the tires on the hydrant servicer was 300 kΩ. With the fueling hoses connected to the tank, the resistance of the overall system (tank trailer and hydrant servicer) to ground before the ground connection was made was 19kΩ. Thus even without the ground connection, the system was effectively grounded through the tires on the hydrant servicer and the tires of the tank, as well as through the Type C Conductive Hose to the hydrant pit valve, since a resistance to ground of < 1MΩ is considered to be sufficient for static purposes (4). The ground cable was connected to the grounding point on the rack for Runs 1 - 8.

Two runs were made at the low flow rate of 450 gpm (0.0284 m^3/s)] and two at 900 gpm (0.0568 m^3/s) - Runs 1-4. The reproducibility of the field strength readings during the high flow rate runs can be seen in Figs. 6 and 7. The field strength is seen to increase as the tank is filled, reaching a maximum of approximately 200 kV/m, and then decay to essentially zero within a minute after flow is stopped. A much more gradual increase in field strength was observed at the lower flow rate (Fig. 8) and the maximum field strength was 124 kV/m, nearly half of what was found at 900 gpm (0.0568 m^3/s). The peak field strengths for all runs and other pertinent test data are summarized in Table 2. These field strengths are consistent with the values reported in the literature for tank truck and refueler loading (6). Field strengths of the order of 140 kV/m were observed in similar tests on actual aircraft fuel tanks (7), and even higher values were found in simulated aircraft fuel tanks (8 and 9).

No discharges were seen on the video displays during these runs despite the rather high field strengths observed on the strip chart recordings, particularly during the final few seconds of fill. These values are representative of what is being seen in the field today when the fuel does not contain a static dissipator additive, i.e., field strengths of several hundred kV/m are obtained in tank trucks and aircraft fuel tanks despite the fact that they are properly bonded and grounded.

No amount of bonding and grounding will prevent this buildup of static charge on the fuel surface (2,10 and 11), which is the primary electrostatic hazard during refueling operations. This hazard can be eliminated only by the use of a static dissipator additive in the fuel or by providing adequate relaxation time between the filter separator and the tank. For tank truck and refueler loading, 30 seconds relaxation time is generally recommended (1,2 and 11), although a value of 100 seconds has been quoted for low conductivity liquids or liquids whose conductivity is unknown (12). Similar relaxation times for aircraft refueling have not been stipulated since the geometry of aircraft fuel tanks and the system design inhibit the development of high potentials (12) with conventional refueling systems.

No voltage buildup on the tank was observed in Runs 1 - 8, as expected, since the entire system was grounded.

During Runs 5 and 6, the current in the bonding cable was found to be -7.8 μA at 550 gpm (0.0347 m^3/s) and -10.3 μA at 870 gpm (0.0549 m^3/s) and these values held constant throughout the run (Fig. 9). On the other hand, almost no current was found to be flowing in the ground wire in Runs 7 and 8 (Fig. 9), indicating that most of the charge on the fuel is neutralized by the current flowing in the bond wire. The process by which this charge neutralization occurs in an aircraft fuel tank is depicted in Fig. 10 which shows that the bond wire provides a path for the charge left on the filter to recombine with the charge on the fuel in the aircraft (10).

As indicated in Table 2, the fuel conductivity was 2-3 pS/m during this series as it was throughout the entire test period. The fuel temperature remained in the range of 45-56°F(7-13°C), while the ambient temperature dipped to 31°F(0°C) and climbed back up to 74°F(23°C) over the course of the test program.

Series II - Tank and Servicer Bonded But Not Grounded

The second series of tests (Runs 9 - 14) was conducted in accordance with the 1990 Edition of NFPA 407 (1), i.e., with the hydrant servicer bonded to the receiving tank but with no ground wire in place. The tires of the hydrant servicer and the rear tires of the tank trailer were resting on concrete, as in the first test series. The field strengths recorded in the receiving tank during these runs were comparable to values obtained when the tank was grounded - compare Fig. 11 with Figs. 6 and 7. The current in the bonding wire, -8.9 μA at 520 gpm (0.0328 m^3/s) and -7.7 μA at 920 gpm (0.0581 m^3/s) (Runs 13 and 14), was in the same range as was found when the system was grounded (Runs 5 and 6). Furthermore, most of the charge on the fuel relaxed within one minute after the flow had stopped (Fig. 11), just as when the tank was grounded (Figs. 6 and 7). Also, no discharges were detected by the video

cameras and no voltage buildup was observed on the receiving tank, just as when the tank was grounded. (A buildup of voltage on the receiving tank, if sufficiently large, could be indicative of a potential ignition hazard or a shock hazard to personnel.) Thus, removal of the ground wire had no effect on the accumulation of charge in the receiving tank, the rate at which the charge relaxed, or on the buildup of static charge on the receiving tank.

Note that the charge density on the incoming fuel and the field strength in the receiving tank were about 20% higher for Runs 13 et seq as compared with the previous runs (Fig. 12 - see Table 2). This is because a different hydrant servicer with somewhat older monitor elements was used for Runs 13 et seq.

An attempt was made to obtain similar data on a refueler using a Dart Refueler with newly-installed Velcon 83 coalescer elements. However, negligible charging was obtained during this run (Run P-2), as indicated by the AO Smith meters, and no field strength was observed in the receiving tank.

Failure to obtain charging of the fuel in this case was attributed to low charging characteristics of the Velcon 83 elements, as observed in previous CRC programs, and to the increased relaxation time in the system downstream of the filters on the Dart Refueler, i.e., 6 seconds as compared with 2 seconds for the hydrant servicer.

Since a sufficiently high charging refueler could not be obtained, the system was modified by installing an isolation flange gasket kit at the hydrant pit valve for the remaining runs (Fig. 13). The isolation flange initially had a resistance of 100 MΩ for Runs 16a - 19, which was improved to 200 MΩ for Runs 20 - 23, thereby effectively eliminating this path to ground and making the hydrant servicer simulate a refueler. (The term 'simulate' in this case refers to the fact that a hydrant servicer is normally connected to the pit value by means of a conductive rubber hose which effectively grounds the servicer, whereas a refueler is not connected to the pit and hence does not have this hose. By installing an isolation flange gasket kit and placing the hose on a teflon pad, this path to ground is eliminated, thereby making the hydrant servicer resemble a refueler).

Series III - Tank and Simulated Refueler Bonded and Grounded

During Run 15a, the "simulated refueler" was bonded and grounded to the receiving tank as per the 1985 Edition of NFPA 407 (5). The field strength recording in the receiving tank (Fig. 14) was comparable to the recording obtained before the isolation flange gasket kit was installed (Fig. 12) and no voltage buildup on the tank was observed.

Series IV - Tank and Simulated Refueler Bonded, not Grounded

Removal of the ground wire in Run 15b had no effect on the field strength (compare Fig. 15 with Fig. 14) or on the current in the bond wire (see Table 2). No voltage buildup on the receiving tank was observed. In other words, the 'simulated refueler' resembled the hydrant servicer in terms of charge generation characteristics and field strength in the receiving tank.

Series V - "Worst Case Scenario" - 'Tank and Simulated Refueler' on Teflon Pads

In order to simulate a "worst case scenario", i.e., a refueling operation in a desert or arctic location where grounding points are difficult or impossible to find and little or no charge can relax to ground through the tires since the ground surface is poorly conducting, the rear two tires of the tank trailer and all of the tires on the hydrant servicer were placed on 1/2 inch (0.013 m) teflon pads. In addition the hose from the hydrant servicer to the pit valve was placed on a teflon sheet to eliminate this path to ground. With the isolation flange gasket kit still in place, the resistance of this system (tank and hydrant servicer) to ground was 200 MΩ. For comparison, the "worst case" resistance to ground for an aircraft was found to be 100 MΩ in one study (13) and 40 MΩ in another (14).

Placing the entire system on teflon pads had no significant effect on charge generation as indicated by the AO Smith Charge Density Meter readings in Table 2, or on the field strength in the receiving tank - compare Fig. 16 and Fig. 15, although a much higher field strength peak was recorded towards the end of Run 16b. As when the tires were on concrete, most of the charge on the fuel relaxed within one minute after flow stopped.

Two runs were conducted with resistances of 10^6 Ω (Run 17) and 10^7 Ω (Run 20) in the grounding circuit to simulate more practical grounding conditions. Again, no significant change in charge generation or in field strength in the receiving tank was observed as compared with the runs in which the tank was properly grounded. Halfway through Run 20, the 10^7 resistor was removed to see if there was any voltage buildup on the receiving tank when it was completely isolated from ground, but bonded to the hydrant servicer. Again, no voltage increase was observed since the bond wire was in place.

In Run 18, an attempt was made to measure the voltage buildup on the tank when it was completely isolated, i.e., with both the bonding and ground wires removed and the wheels resting on teflon pads. For this run, the AO Smith Meters were also removed from the system to preclude any extraneous paths to ground. Under these conditions, the voltage on the receiving tank rapidly rose to 600-800 V. Unfortunately, the voltage obtained was at the lower end of sensitivity for the voltmeter used and the value obtained, approximately 600 - 800 V, is not very accurate. For comparison, the voltage calculated from the charging current is 2500 V for this run.

A final run was conducted (Run 19) with the wheels of both vehicles on teflon, but with the ground wire in place. A comparison of this run (Fig. 17) with Run 16 in which the ground wire was removed (Fig. 16) showed a somewhat higher field strength towards the end of the run for the grounded system. However, no significance is attached to this observation since the runs were conducted on consecutive days when there was a general trend towards higher charging with time.

Run 21 was interupted due to mechanical difficulties and hence only limited data, corresponding to a flow of 3000 gallons of fuel, were obtained. Therefore, the data from this run were not included in Table 2, but the charge relaxation data are given in Table 3.

Demonstrations

Runs 22 and 23 were conducted as part of the demonstration on the final test day. Again, the worst case scenario was employed, i.e., refueling of an aircraft in the arctic or the desert where there can be little or no charge relaxation through the tires. For this purpose, all of the wheels, both of the hydrant servicer and of the tank trailer were on teflon pads, 1/2 inch (0.013 m) thick, and the isolation flange gasket kit was in place. The resistance to ground of this system was 200 MΩ.

For Run 22, the hydrant cart and tank were bonded and grounded as per the 1985 Edition of NFPA 407 [5]. The charge density on the incoming fuel, the field strength in the receiving tank* and the current flowing in the bond wire were in the same ranges as in the previous runs and no voltage buildup was observed on the receiving tank. After 5000 gallon (19.0 m^3) of fuel had been delivered, the ground wire was removed but the bond wire left in place. No change in the field strength (Fig. 18) or in the bonding current was observed with the ground wire removed. Again, the charge on the fuel relaxed in about a minute.

For Run 23, the AO Smith meters and the Keithly Picoammeter were taken out of the system to eliminate paths to ground through the instruments. The ground wire was removed and the bond wire was disconnected. The only instrument connected to the system at the start of the run was the electrostatic voltmeter. Flow was started at 900 gpm (0.0568 m^3/s) and within 10 seconds the voltmeter reached 125 V demonstrating how quickly the voltage on the tank builds up when the system is unbonded and ungrounded. (In a previous run (Run 18) it was demonstrated that this voltage would ultimately reach about 600-800V). The flow was stopped, the bond wire connected to the tank and the flow restarted. The field strength in the tank (Fig. 19) was similar to Run 22 when the tank was bonded and grounded and the charge relaxation was comparable.* No voltage buildup on the tank was observed as long as the bond wire was connected. About 10 seconds after flow was stopped, the bond wire was disconnected, just as in an aircraft refueling operation. As expected, there was no voltage buildup on the receiving tank since the charge on the fuel had been neutralized by the current flowing in the bond wire.

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* **Note:** To properly compare Figs. 17 and 18, one should overlay the charge charge relaxation portion of Fig. 17, i.e., the point marked 'STOP' on Fig. 17 over the same mark on Fig. 18. This is because a wire to the Keithley Picommeter was broken before the start of Run 22, but the break wasn't discovered for about 60 seconds at which time there was approximately 900 gallons of fuel on the tank. The wire was repaired and the run was continued. Therefore, comparison of the end portions of the field strength curves is proper since the fuel levels in the tanks were the same during this portion of the run.

Charge Relaxation

In all cases, i.e., when the hydrant servicer and receiving tank were bonded and grounded or bonded only, the field strength in the tank decreased to essentially zero in 60 seconds or less. Plots of the field strength in the tank after the flow was stopped versus time indicated that the decay of charge was exponential (Fig. 20), in accordance with theory. Calculations of the effective conductivity from the charge decay plots, as shown in Table 3; gave an average effective conductivity of about 1.0 pS/m. In other words, the charge decayed about half as fast as one would predict from the measured conductivity.

Aircraft Tire Resistance Measurements

Measurements were made of the resistance to ground of aircraft parked on concrete and on asphalt at the following airports: Denver Stapleton, San Francisco International and Phoenix Sky Harbor. The aircraft were representative of the major types in use by airlines throughout the world and included some mothballed aircraft. The tires on individual aircraft usually involved a mix of manufacturers, as shown in Tables 4 and 5. The age of tires varied considerably from nearly new to quite old, as in the case of the mothballed aircraft, and on some aircraft recapped tires were used.

The resistance to ground of operational aircraft when parked at the gate, at various ramp locations where grounding points could be found or in hangars varied from 0.001 to 0.5 MΩ - see Table 4. No correlation with aircraft size or type could be made since such a comparison would involve moving aircraft to the same location for measurements. Since all of these values are less than 1MΩ, the aircraft could be considered to be grounded through their tires from the standpoint of static electricity, even without a ground wire being attached to the aircraft.

Measurements were also made on some mothballed aircraft which were parked at remote locations, primarily to obtain more data on asphalt surfaces - see Table 5. The tires on all of these aircraft appeared to be quite old and the asphalt surfaces were badly weathered. The only available grounding points were aircraft tie downs (concrete reinforcement bars). Nevertheless, low resistances were obtained (0.01 to 0.1 MΩ) as indicated in Table 5. There was only one exception, a DC9 aircraft parked in a remote location on a dry concrete surface. A value of 2.3 MΩ was obtained on this aircraft which was the highest value found in this study. However, no particular significance is attached to this finding since the tires were obviously old, the grounding point somewhat questionable and the aircraft wasn't parked in a normal refueling location.

These results indicate that the aircraft tires measured were sufficiently conductive to bleed off residual static charge generated in flight or as a result of air-blown dust or snow particles. This is not an indication that aircraft tires can always be relied upon for adequate static grounding in lieu of separate connections. However, as demonstrated above, neither a conductive path through the tires nor the use of a ground wire is required to dissipate static charge generated during aircraft refueling or tank truck loading. Nevertheless, as indicated in NFPA 407 (1), if ground support equipment requiring electrical earthing is connected to the aircraft or if other operations are conducted that require electrical earthing, then separate connections must be made for this purpose.

SUMMARY AND CONCLUSIONS

1. When the hydrant servicer and receiving tank were properly bonded and grounded as per the 1985 Edition of NFPA 407 (5), field strengths of several hundred kV/m were observed in the tank. In other words, bonding and grounding do not prevent the accumulation of charge in the tank. The field strength was found to decay to essentially zero within one minute after flow was stopped as the charge on the fuel relaxed. There was no voltage build up on the tank, as expected, since the tank was grounded.

2. Removal of the ground wire had no effect on:

   (a) charge generation

   (b) field strength in the receiving tank

   (c) voltage buildup on the tank during filling or

   (d) the rate at which the charge relaxes after flow is stopped,

   as long as the bond wire was in place. This conclusion was found to be valid when the tires of both the hydrant servicer (or refueler) were resting on a concrete surface, as in most refueling operations, or were on teflon pads, which simulate a worst case scenario in which charge cannot relax through the tires.

3. When the hydrant servicer was connected to the hydrant pit valve using Type C conductive hose and no isolation flange gasket kit or ground connection was used and with the tires on concrete, the resistance to ground was found to be 19 kΩ. Thus, even without a separate ground connection, the hydrant cart was effectively grounded since, for purposes of static electricity, a resistance to ground of < 1 MΩ is sufficient.

4. No discharges were detected in any of the runs, regardless of whether or not the vehicles were bonded and/or grounded.

5. If no bond wire and no ground wire were used and the tank was electrically isolated, i.e., on teflon pads and with an effective isolation flange gasket kit in place, the voltage on the receiving tank increased rapidly (0-125V in 10 seconds). This voltage would ultimately reach a limiting value, which may be in excess of 1000 volts, depending upon the charging current and the resistance of the system to ground. These tests reaffirm the position taken in the 1990 Edition of NFPA 407 that bonding is required and, by itself, is sufficient to prevent voltage build-up on the receiving tank.

6. Measurements on operational aircraft parked at the gate, at various ramp locations or in a hanger indicated that resistances to ground were sufficiently low to assure that, with respect to static electricity, the aircraft were effectively grounded through their tires. However, as demonstrated in this study, neither a conductive path through the tires nor the use of a ground wire is required to dissipate the static charge generated during aircraft refueling or tank truck loading. A separate connection to ground may be required if other operations are being performed which require elecrical earthing.

7. These tests demonstrated that deletion of the requirement for grounding during aircraft refueling and tank truck loading, as recommended in NFPA 407 1990 Edition (1), does not result in an increased electrostatic hazard as long as the bond wire is in place. The bond wire does provide a path for the charges separated at the filter to recombine with the charges in the fuel tank, thereby permitting charge neutralization to occur in the absence of a ground wire.

8. Finally, no amount of bonding and grounding will eliminate the primary electrostatic hazard during these operations, i.e., an electrostatic discharge in the vapor space of the tank. This hazard can be eliminated only by the use of a static dissipator additive in the fuel or by providing adequate relaxation time between the filter separator and the tank. (For tank truck and refueler loading, at least 30 seconds relaxation time is generally recommended: no comparable value has been stipulated for aircraft refueling.

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11. W. M. Bustin and W. G. Dukek, "Electrostatic Hazards in the Petroleum Industry," Research Studies Press Ltd, Letchworth, Hertsfordshire, England, 1983.

12. H. L. Walmsley, "The Avoidance of Electrostatic Hazards in the Petroleum Industry," J. Electrostatics, 27, 1-200 (1992).

13. C. Kontji, "Report on the Study 3886 PHE Bonding and Grounding Requirements in Aircraft POL Servicing Operations," TUV Rheinland, Cologne, FRG, 13 Sept 1982.

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TABLES

AND

FIGURES

Table 1 - Test Matrix

Run	Hydr. Ser. No.	Flow Rate GPM	Electrostatic Field Meter	Discharge Detector	A. O. Smith Charge Density Meters	Keithley Electrometer			Electro-static Voltmeter	Teflon Pad	Resis-tor
						1	2	3			
Series I - Tank and Servicer Bonded and Grounded as Per NFPA 407 (1985)											
1	34	450	x	x	x						
2	34	450	X	x	x				x		
3	34	900	x	x	x						
4	34	900	x	x	x				x		
5	34	450	x	x	x	x			x		
6	34	900	x	x	x	x					
7	34	450	x	x	x		x				
8	34	900	x	x	x		x				
Series II - Tank and Servicer Bonded, But Not Grounded, as Per NFPA 407 (1990)											
9	34	450	x	x	x						
10	34	450	x	x	x				x		
11	34	900	x	x	x						
12	34	900	x	x	x				x		
13	417	450	x	x	x	x					
14	417	900	x	x	x	x					

Table 1 (continued)

Run	Hydr. Ser. No.	Flow Rate GPM	Electrostatic Field Meter	Discharge Detector	A. O. Smith Charge Density Meters	Keithley Electrometer			Electro-static Voltmeter	Teflon Pad	Resis-tor
						1	2	3			
Series III - Tank and Simulated Refueler Bonded and Grounded as Per NFPA 407 (1985)											
15a	417	900	x	x	x	x			x		
Series IV - Tank and Simulated Refueler Bonded, But Not Grounded, as Per NFPA 407 (1990)											
15b	417	900	x	x	x	x			x		
Series V - "Worst Case Scenario", Tank and Simulated Refueler on Teflon Pads											
16a	417	900	x	x	x	x			x	x	
16b	417	900	x	x		x			x	x	
17	417	900	x	x		x			x	x	10^6
18	417	900	x	x					x	x	
19	417	900	x	x	x	x			x	x	
20	417	900	x	x					x	x	10^7
21	417	900	x	x	x				x		
Demonstrations:											
22	417	900	x	x	x	x			x	x	
23	417	900	x	x					x	x	

Table 2 - Summary of Test Results

Run	Fuel Temp °F	Fuel Temp °C	Fuel Cond pS/m	Flow Rate GPM	Flow Rate m^3/S	Peak Fields Strength kV/m	Discharges Detected	Charge Density $\mu C/m^3/S$ Meter 1	Charge Density $\mu C/m^3/S$ Meter 2	Current in Bond Wire μA	Current in Ground Wire μA	Electro-static Voltmtr. Volts	Ambient Temp. °F	Ambient Temp. °C
Series I - Tank and Servicer Bonded and Grounded as Per NFPA 407 (1985). Tires on Concrete														
1	54	12	2	550	0.0347	124	No	194	ND	†	†	0		
2	54	12	2	550	0.0347	127	No	195	ND	†	†	0		
3	55	13	3	910	0.0574	226	No	176	290	†	†	0		
4	54	12	2	890	0.0562	ND	No	198	302	†	†	0		
5	54	12	2	550	0.0347	170	No	195	ND	-7.8	†	0		
6	49	9	2	870	0.0549	214	No	195	309	-10.3	†	0		
7	52	11	2	560	0.0353	106	No	348	ND	†	0.1	0		
8	54	12	2	890	0.0562	188	No	197	345	†	0.2	0		
Series II - Tank and Servicer Bonded, But Not Grounded, as Per NFPA 407 (1990). Tires on Concrete														
9	55	13	3	550	0.0347	117	No	231	ND	†	–	0	51	10
10	54	12	2	560	0.0353	107	No	216	ND	†	–	0	56	13
11	56	13	2	900	0.0568	205	No	207	206	†	–	0	53	12
12	55	13	2	900	0.0568	278	No	204	206	†	–	0	51	10
13*	45	7	2	520	0.0328	146	No	317	ND	-8.7	–	0	31	0
14*	45	7	2	920	0.0581	290	No	338	ND	-7.7	–	0	34	1

Table 2 (continued)

Run	Fuel Temp °F	Fuel Temp °C	Fuel Cond pS/m	Flow Rate GPM	Flow Rate m^3/S	Peak Fields Strength kV/m	Discharges Detected	Charge Density $\mu C/m^3/S$ Meter 1	Charge Density $\mu C/m^3/S$ Meter 2	Current in Bond Wire μA	Current in Ground Wire μA	Electro-static Voltmtr. Volts	Ambient Temp. °F	Ambient Temp. °C
Series III - Tank and Simulated Refueler Bonded and Grounded as Per NFPA 407 (1985), Tires on Concrete														
15a*	52	11	2	900	0.0568	313	No	450	388	11.3	†	0	52	11
Series IV - Tank and Simulated Refueler Bonded, But Not Grounded, as Per NFPA 407 (1990), Tires on Concrete														
15b*	52	11	2	900	0.0568	301	No	432	344	10.4	–	0	56	13
Series V - "WorstCase Scenario", Tank and Simulated Refueler Tires on Teflon Pads														
16a*	52	11	2	910	0.0574	319	No	475	436	-11.6	–	0	45	7
16b*	52	11	2	920	0.0581	445	No	**	**	-12.4	–	0	40	4
17*	51	10	2	920	0.0581	322	No	**	**	-12.5	****	0	38	3
18*	49	9	2	820	0.0517	415	No	**	**	–	–	600-800	37	3
19*	52	11	2	880	0.0555	424	No	438	370	-10.8	†	0	62	17
20*	53	12	2	880	0.0555	342	No	**	**	–	*****	0	68	20
Dart Refueler														
P-2	45	7	2			0	No	0	0	†	†	0		
Demonstrations, Tank and Simulated Refueler Tires on Teflon														
22*	53	12	2	900	0.0568	421	No	ND	ND	-12	†	0	74	23
23*	53	12	2	900	0.0568	442	No	**	**	†	–	***	74	23

* - Runs 1 - 12 were made with Hydrant Servicer 34, Runs 13 - 23 were made with Hydrant Servicer 417.
** - AO Smith Meters were removed from the system to preclude any extrancous grounding paths dumg the Bonding Current Measurements.
*** - When both the bond wire and the ground wire were removed, the voltage reached 124 V in 10 seconds. When the bond wire was connected, no voltage was recorded.
**** - 10^6 Resistor in ground circuit.
***** - 10^7 Resistor in ground circuit.

† = Wire in place, no ommeter in circuit

– = No wire in place

ND = No data. At low flow rates, only one refueling hose and one A. O. Smith meter were used.

Table 3 - Effective Conductivity as Calculated from Charge Decay Curves

Run No.	Effective Conductivity, pS/m	Measured Conductivity, pS/m	Bonded and Grounded	Bonded Only
6	1.16	2	X	
8	0.97	2	X	
11	0.95	2		X
12	1.37	2		X
14	0.91	2		X
15B	0.92	2	X	
15A	0.97	2		X
16A	0.95	2		X
17	1.29	2		X
18	0.94	2		X
19	0.80	2	X	
20	0.82	2	X	
21	1.16	2		X
22	1.11	2	X	
23	0.97	2		X
	AV. 1.02			

Table 4 - Resistance of Aircraft to Ground (Operational Aircraft)

Aircraft Type	Tire Manufacturers[a]										Resistance (MΩ)	Surface
	Nose Gear		Left Undercarriage				Right Undercarriage					
	L	R	LF	LR	RF	RR	LF	LR	RF	RR		
Stapleton International Airport, Denver, CO, 11/8/91, 74°F												
727	GY	GY	GY	-	BS	-	GR	-	TH*	-	0.005	
727	GY	GR	GY	-	GR	-	GR	-	TH*	-	0.001	
727	GR	GR	TH	-	BS	-	GR	-	TH*	-	0.005	
737-200	GY	GY	GY	-	GY	-	GY	-	GY	-	0.015	
San Francisco International Airport, San Francisco, CA, 4/27/92, 74°F												
737-222	GY	GY	BS	-	GY	-	GY	-	GY	-	0.02	Broken blacktop w/ grass growing through
DC10-10	GY	GR	BS	BS	GY	GY	BS	GY	GY	GY	0.09	Nose wheels on dry blacktop, all others on dry concrete.
737-222	GY	GY	GY	-	BS	-	GY	-	GY	-	0.05	Slightly broken blacktop
737-322	GR	GR	GY	-	GR	-	GR	-	BS	-	0.06	Dry concrete
747-422	GY	BS	GY*	BS*	GY*	BS	BS	BS	BS	GY	0.004	Dry concrete
(aft undercarriage)	-	-	GY*	GY	BS	BS	GY	GY	BS	BS		
757-222	DL	DL	BS	BS	BS	BS	BS	BS	BS	BS	0.02	Nose wheels on dry blacktop, all others on dry concrete.
Sky Harbor Airport, Phoenix, AZ, 4/28/92 (afternoon), 104°F												
737-200	GY	GR	GR	-	GR	-	GR	-	GR	-	0.015	Sealed concrete, inside hangar
Sky Harbor Airport, Phoenix, AZ, 4/28/92 (night), ca. 80°F												
757	BS	GY	GY	GY	GY	GY	GY	GY	GY	GY	0.3	Dry blacktop
Dash 8-102	GR	GR	GR	-	GR	-	GR	-	GR	-	0.3	Dry concrete
737	GY	GY	GY	-	GY	-	GY	-	GY	-	0.25	Dry concrete
DC10	GR	GY	GR	GR	GY	GR	GR	GR	GR	GR	0.5	Dry concrete

[a] Key: BS = Bridgestone; DL = Dunlop; GR = Goodrich; GY = Goodyear; TH = Thompson
* Recapped Tire

Table 5 - Resistance of Aircraft to Ground (Mothballed Aircraft)

Aircraft Type	Tire Manufacturers[a]										Resistance	Surface
	Nose Gear		Left Undercarriage				Right Undercarriage					
	L	R	LF	LR	RF	RR	LF	LR	RF	RR	(MΩ)	
Sky Harbor Airport, Phoenix, AZ, 4/28/92 (afternoon), 104°F												
Fokker 100	GY	GY	GY	-	GY	-	GY	-	GY	-	0.01	Dry blacktop, repaired w/ tar.
Fokker 100	GY	GY	GY	-	GY	-	GY	-	GY	-	0.01	Dry blacktop, repaired w/ tar.
Fokker 100	GY	GY	GY	-	GY	-	GY	-	GY	-	0.05	Dry blacktop, repaired w/ tar.
737	GY	GY	GY	-	GY	-	GY	-	GY	-	0.1	Dry blacktop, repaired w/ tar.
DC9	GR	GR	GR	-	GR	-	GR	-	GR	-	2.3	Dry concrete

[a] Key: BS = Bridgestone; DL = Dunlop; GR = Goodrich; GY = Goodyear; TH = Thompson

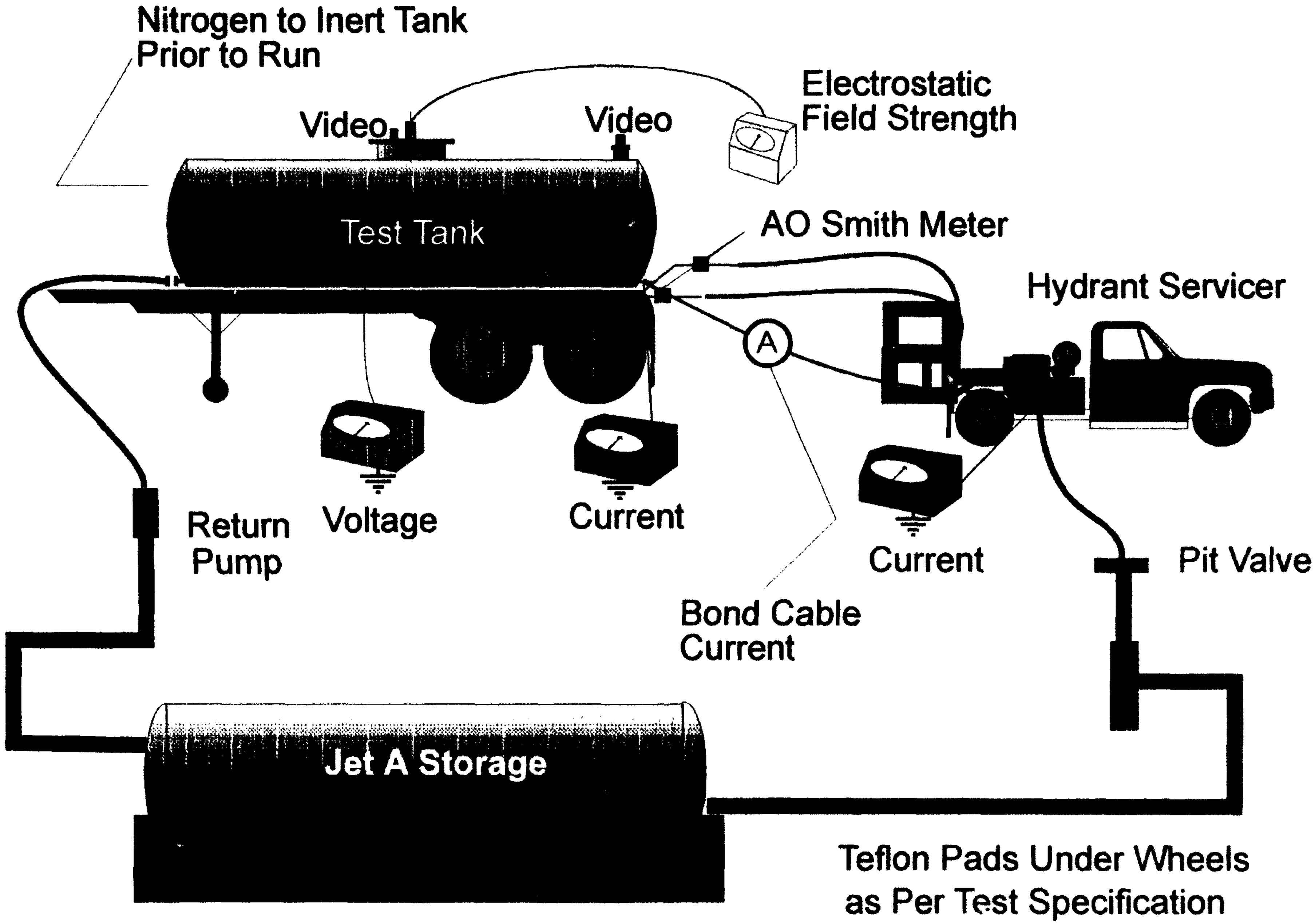


Figure 1 -- Experimental Set-Up for Bonding & Grounding Study

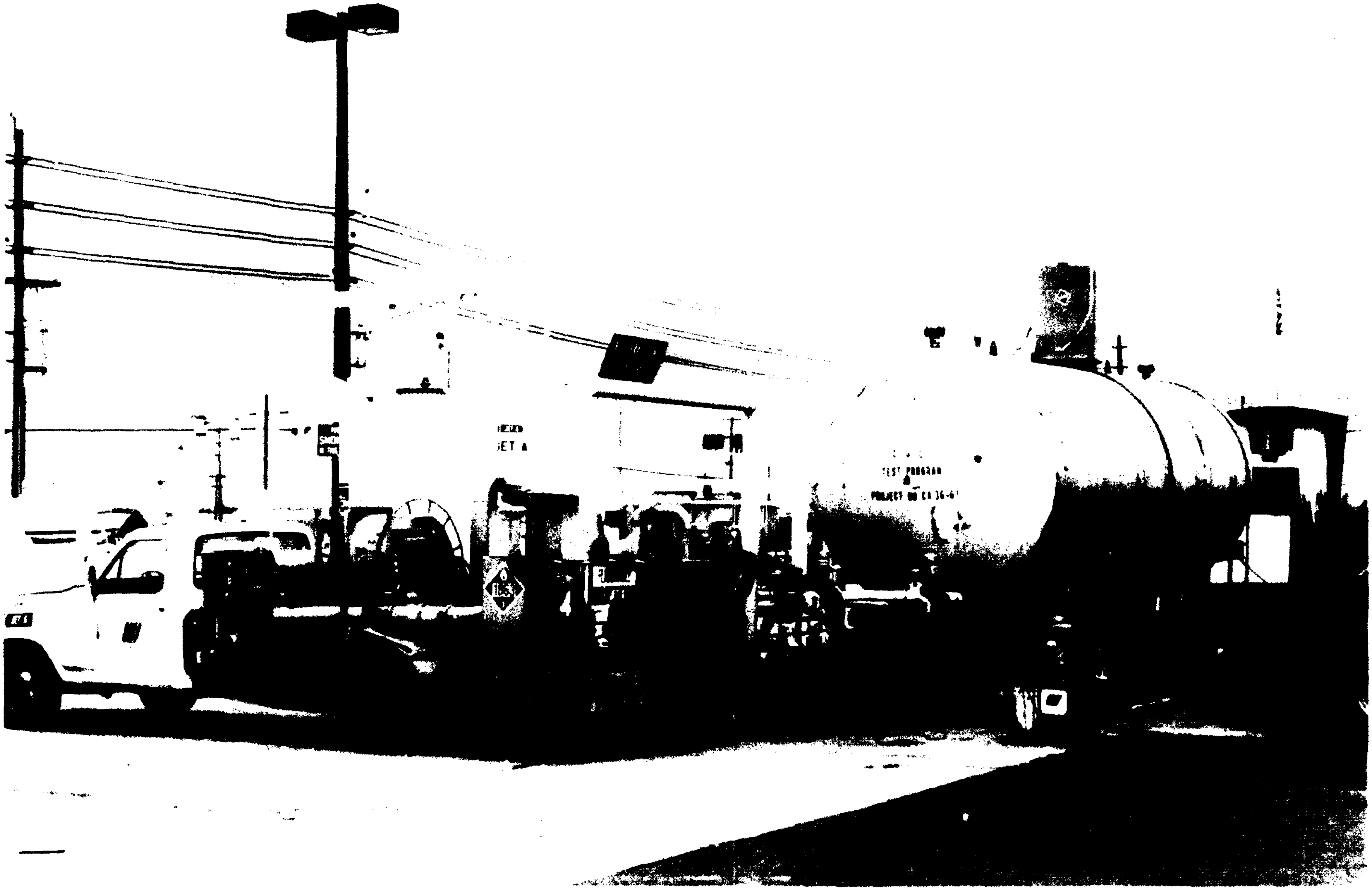


Fig 2. Hydrant Servicer and Receiving Tank

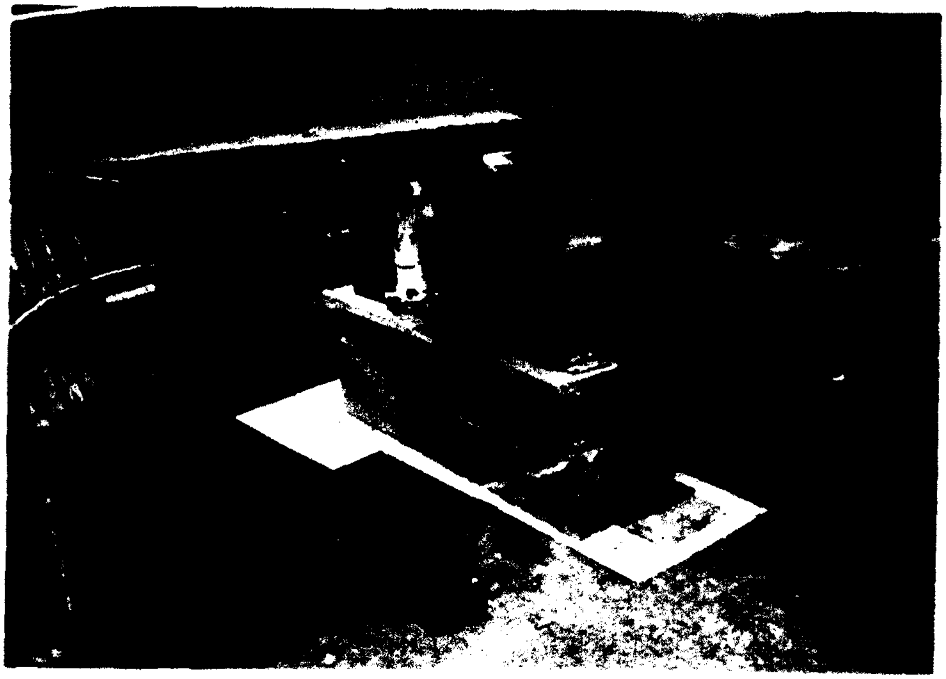


Fig 3. Front Trailer Supports on Teflon Pad

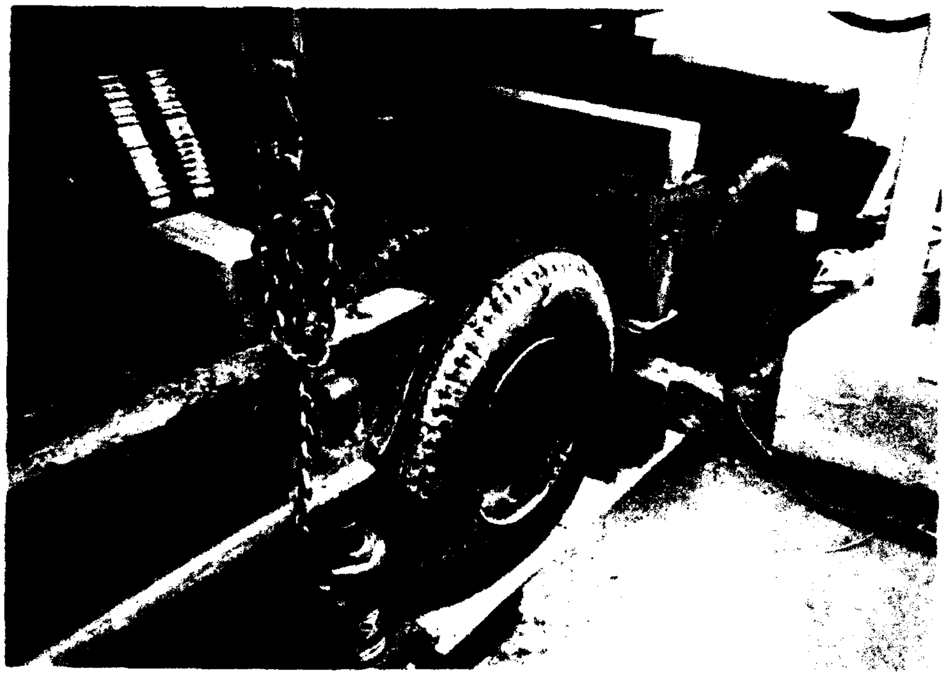


Fig 4. Front Trailer Wheels on Teflon Pads and Rear Wheels on Concrete

Figure 5--
Calibration Curve for Electrostatic Field Meter

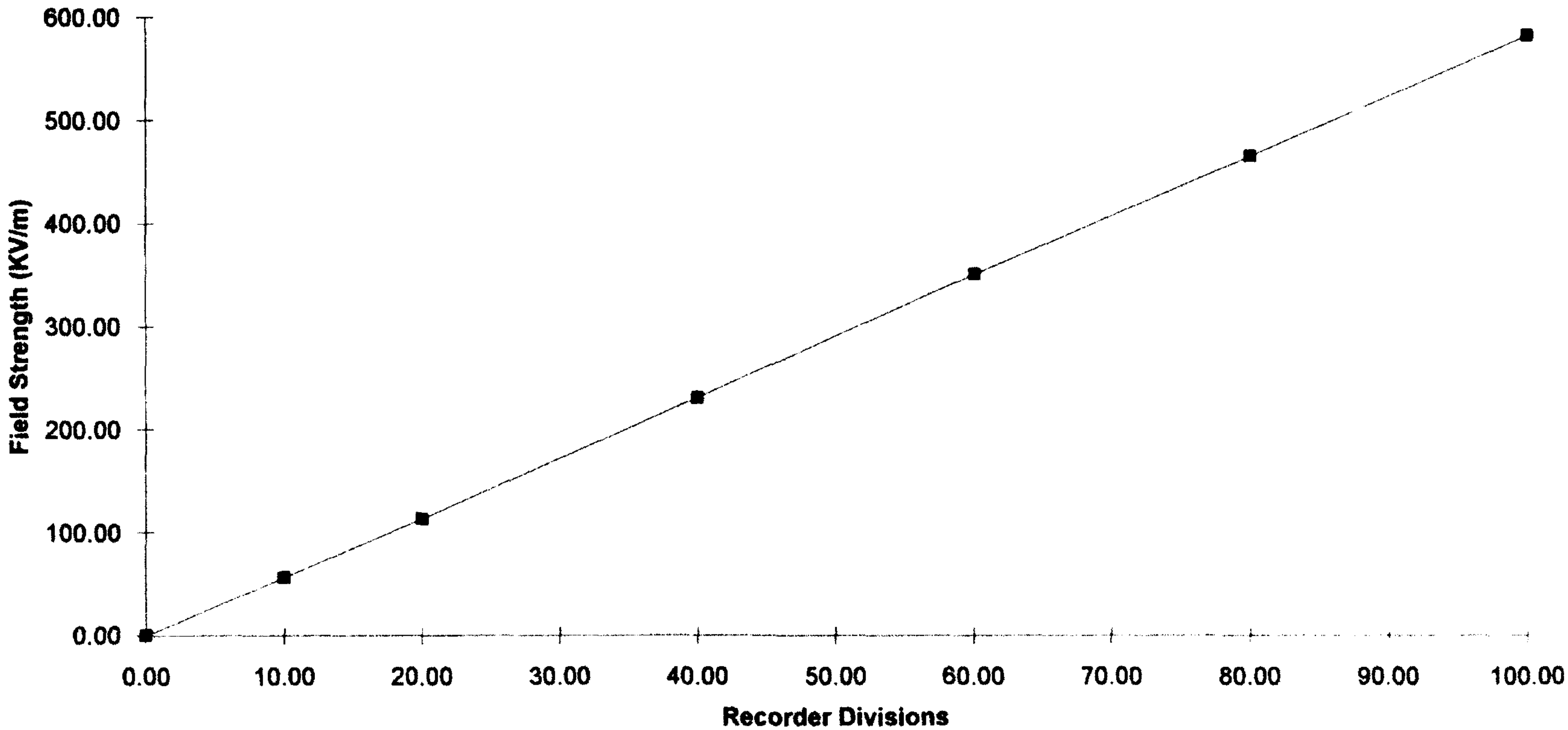


Figure 6--
Field Strength in Tank
RUN 6 -- Hydrant Servicer & Tank Bonded & Grounded
Flow Rate = 870 GPM (Tires on Concrete)

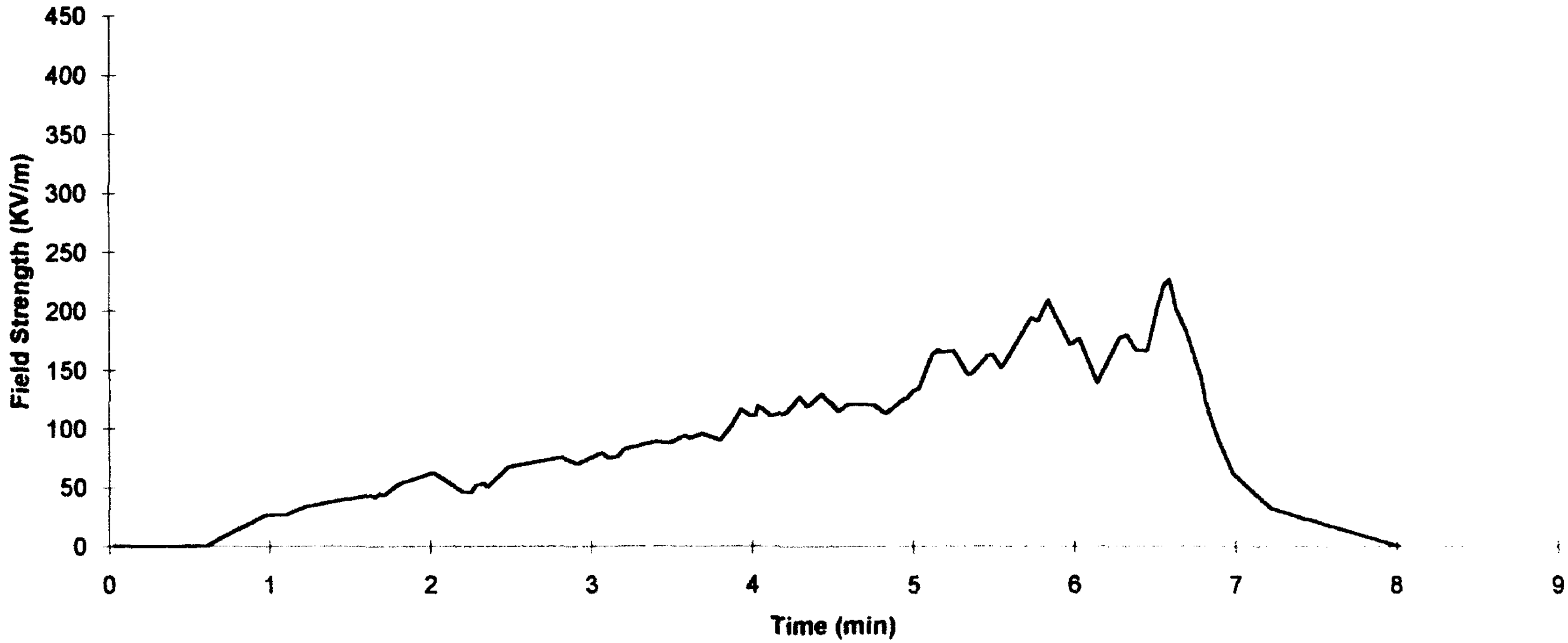


Figure 7--
Field Strength in Tank
RUN 8 -- Hydrant Servicer & Tank Bonded & Grounded
Flow Rate = 890 GPM (Tires on Concrete)

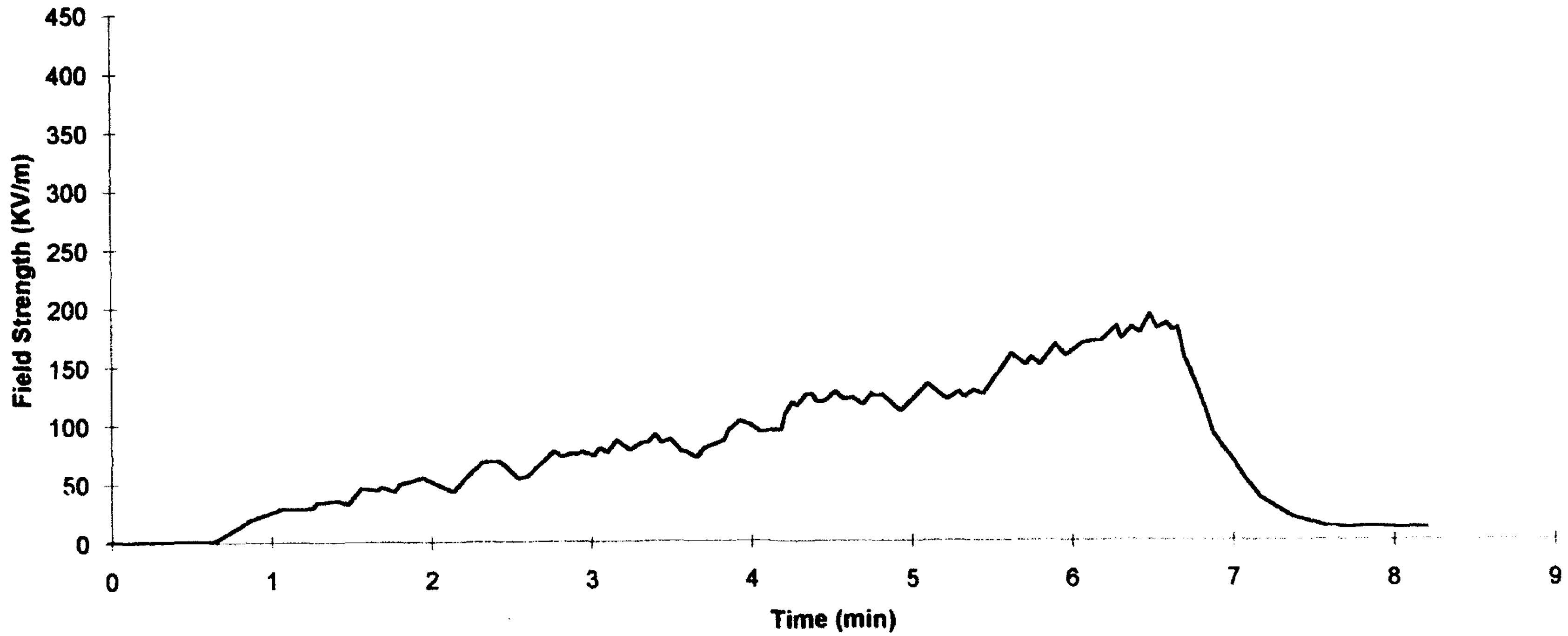


Figure 8--
Field Strength in Tank
RUN 1 -- Hydrant Servicer & Tank Bonded & Grounded
Flow Rate =550 GPM (Tires on Concrete)

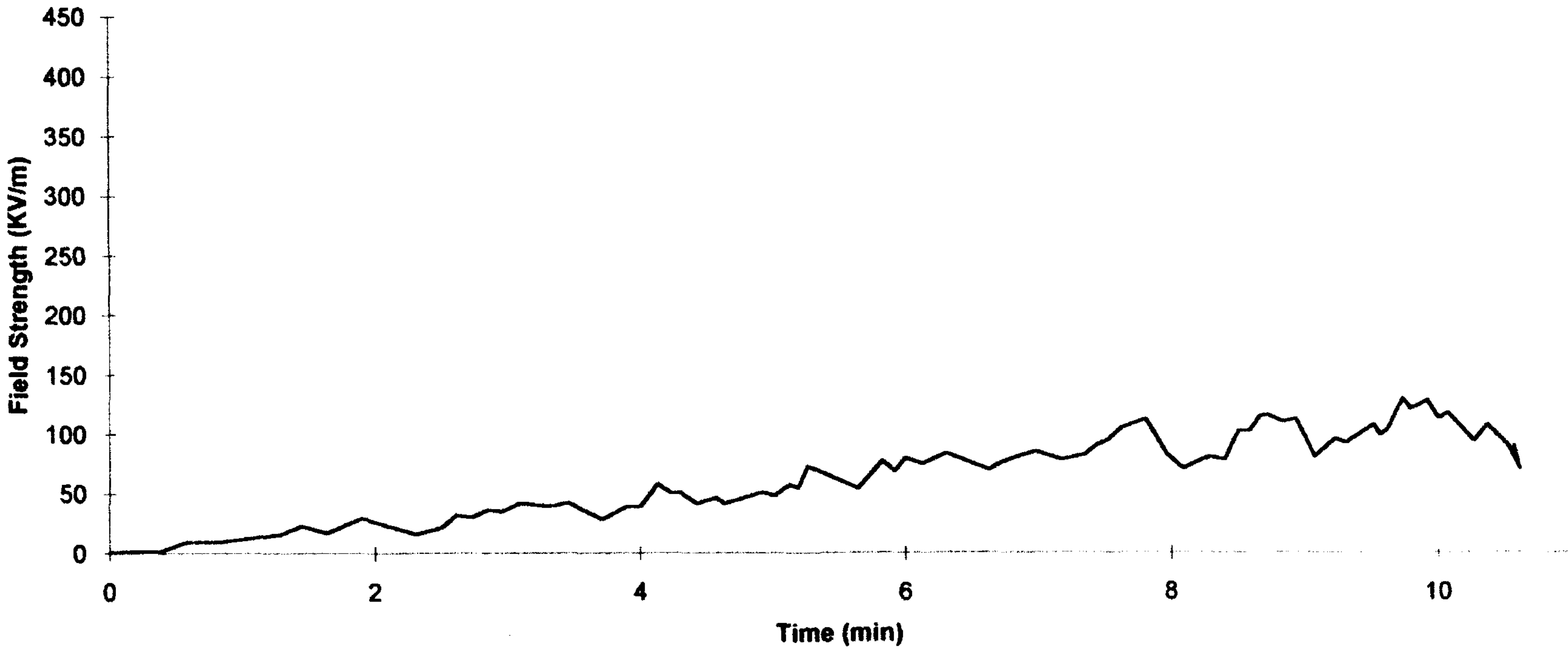
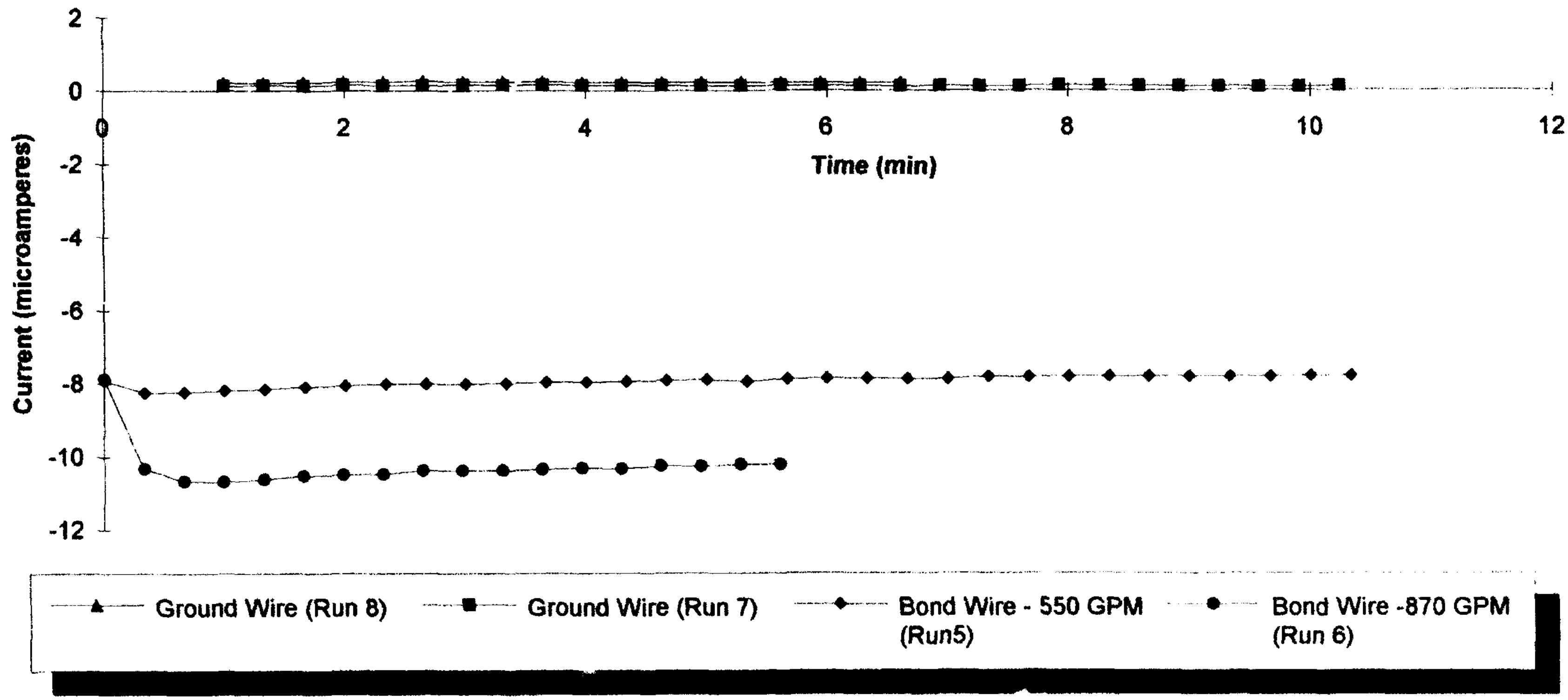


Figure 9 --
Current in Bond & Ground Wires
During Runs 6 and 8



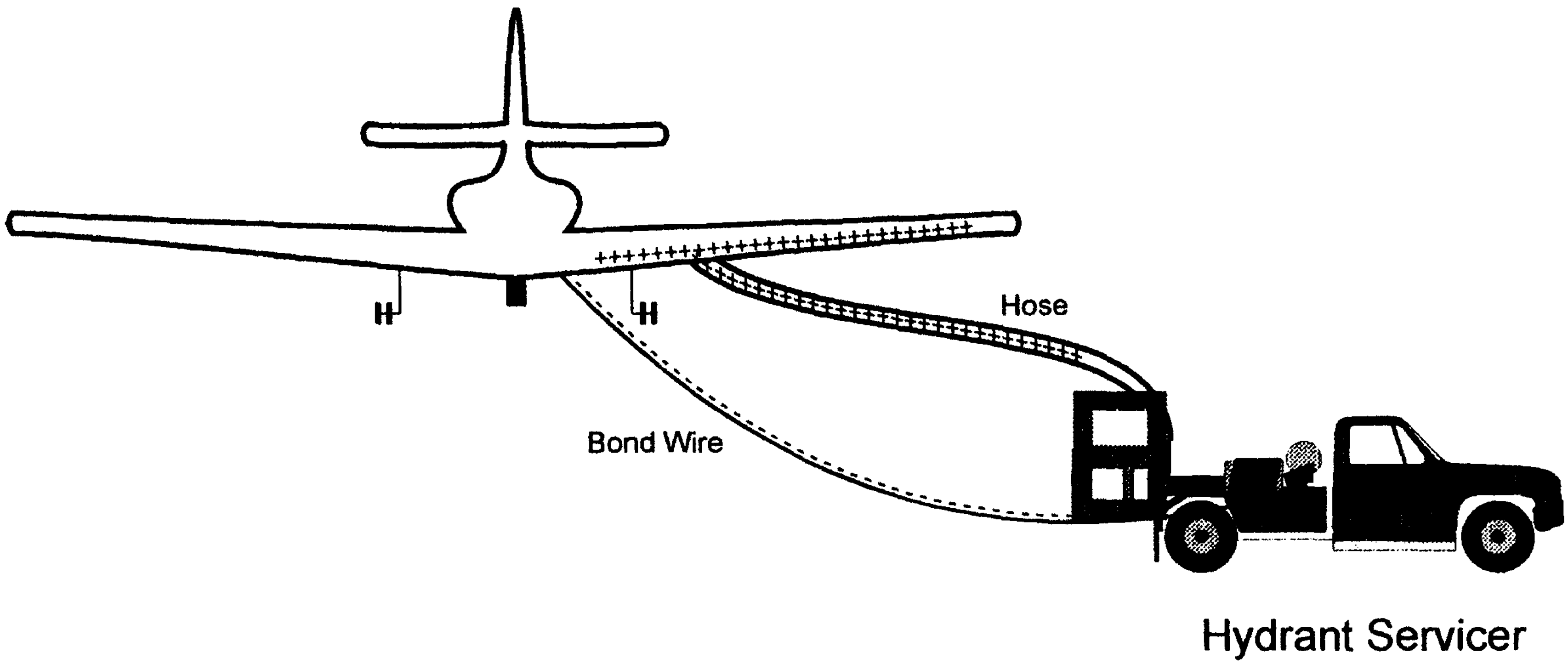


Figure 10 -- Bond Wire Provides Path for Negative Charges Left on Filter/Separator by Fuel Charging Process to Combine with Positive Charges in Fuel, Thereby Precluding the Need for a Separate Ground Wire

Figure 11--
Field Strength in Tank
RUN 11 -- Hydrant Servicer & Tank Bonded NOT Grounded
Flow Rate =900 GPM (Tires on Concrete)

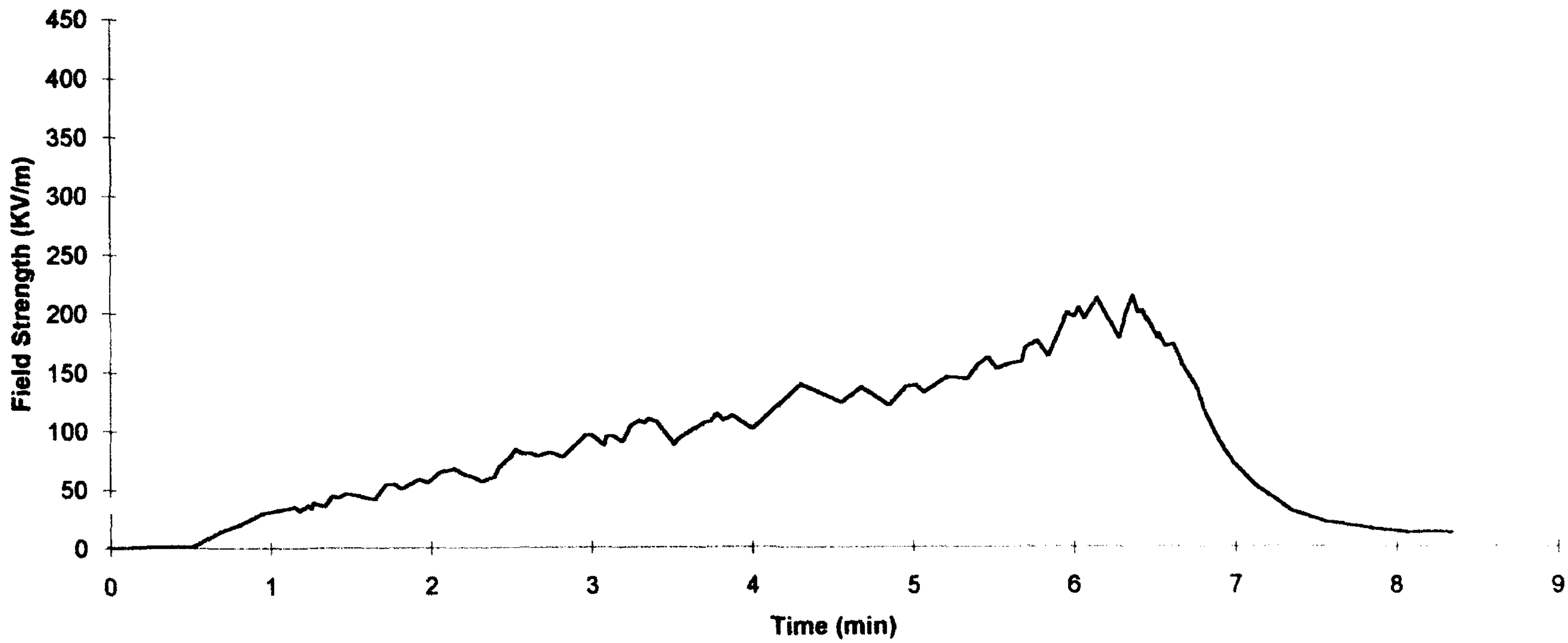
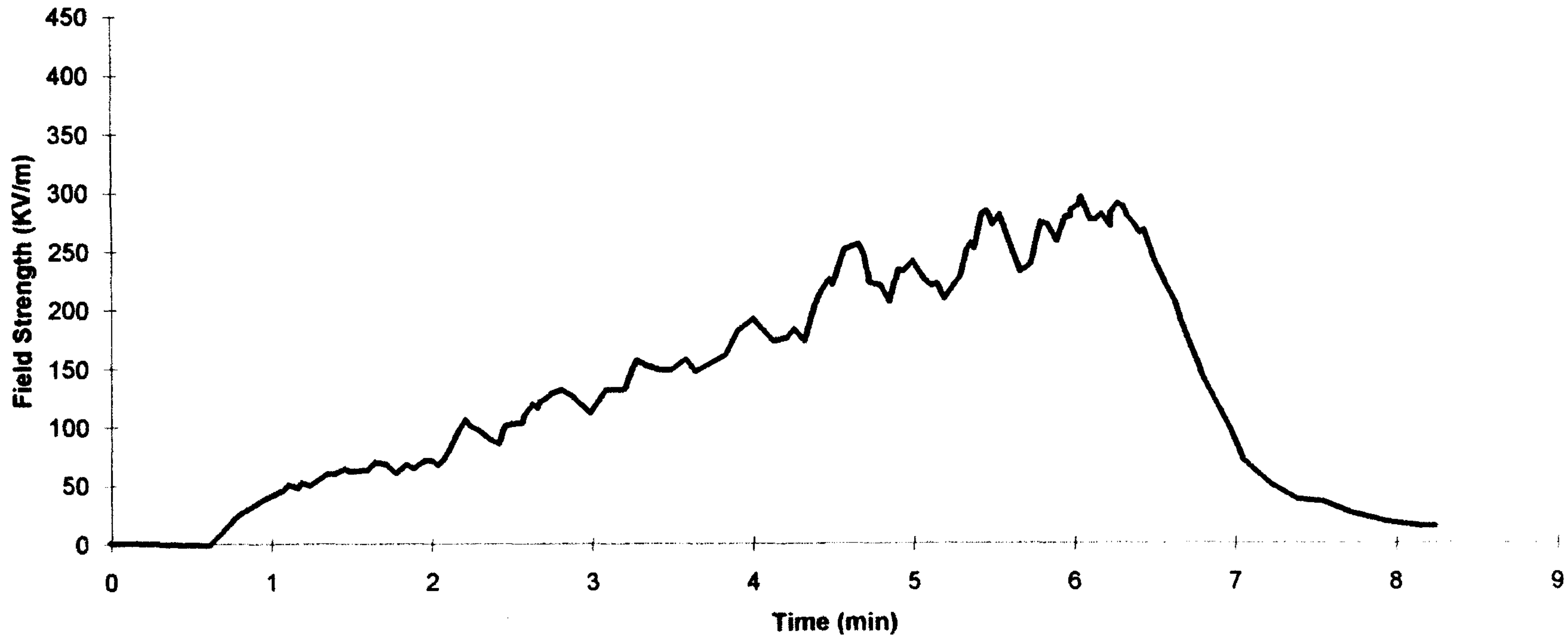


Figure 12--
Field Strength in Tank
RUN 14 -- Hydrant Servicer & Tank Bonded NOT Grounded
Flow Rate =920 GPM (Tires on Concrete)



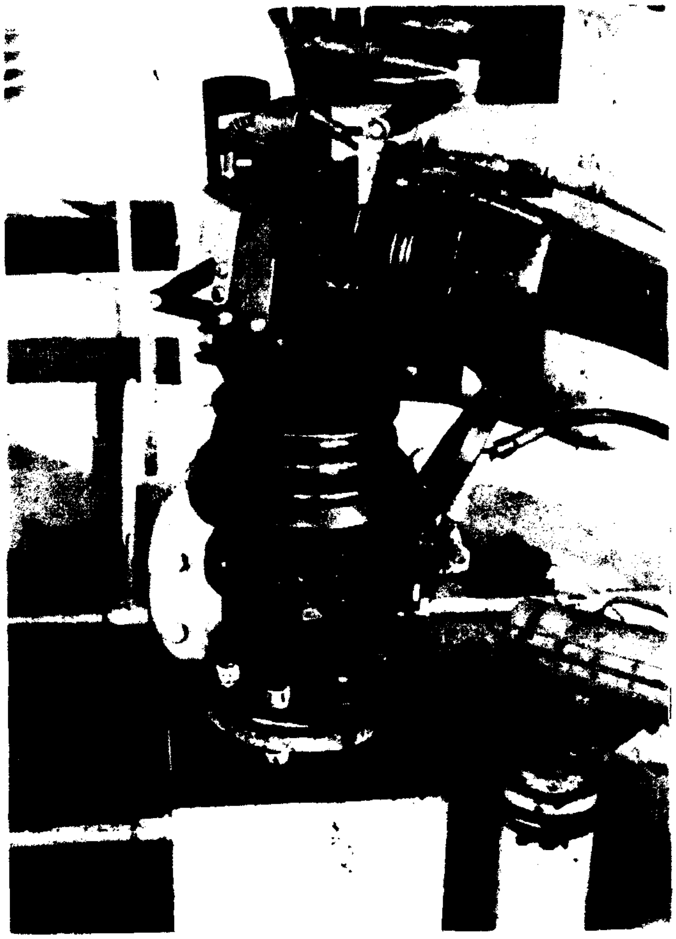


Fig 13. Installation of Isolation Flange at Hydrant Pit Valve

Figure 14--
Field Strength in Tank
RUN 15A -- Simulated Refueler & Tank Bonded & Grounded
Flow Rate =900 GPM (Tires on Concrete)

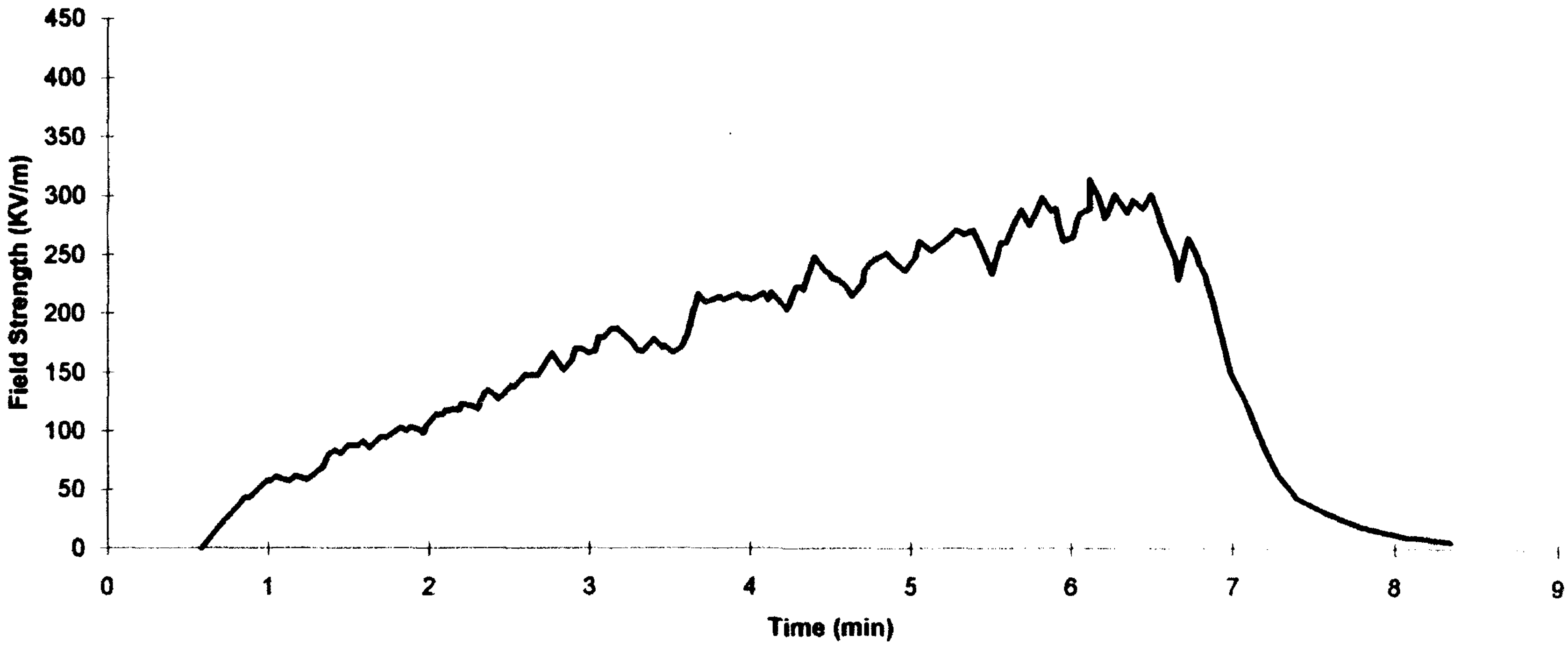


Figure 15--
Field Strength in Tank
RUN 15B -- Simulated Refueler & Tank Bonded NOT Grounded
Flow Rate =900 GPM (Tires on Concrete)

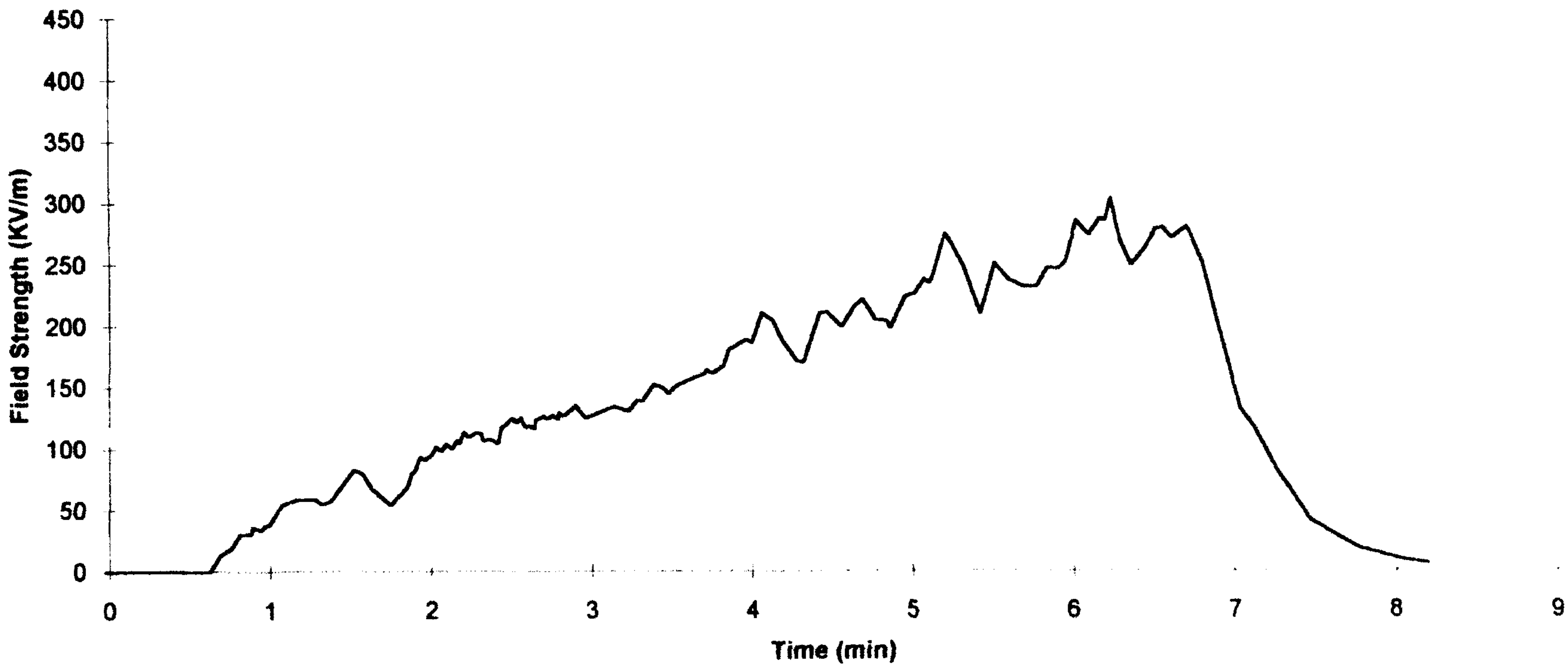


Figure 16--
Field Strength in Tank
RUN 16A -- Simulated Refueler & Tank Bonded NOT Grounded
Flow Rate =910 GPM (Tires on Teflon)

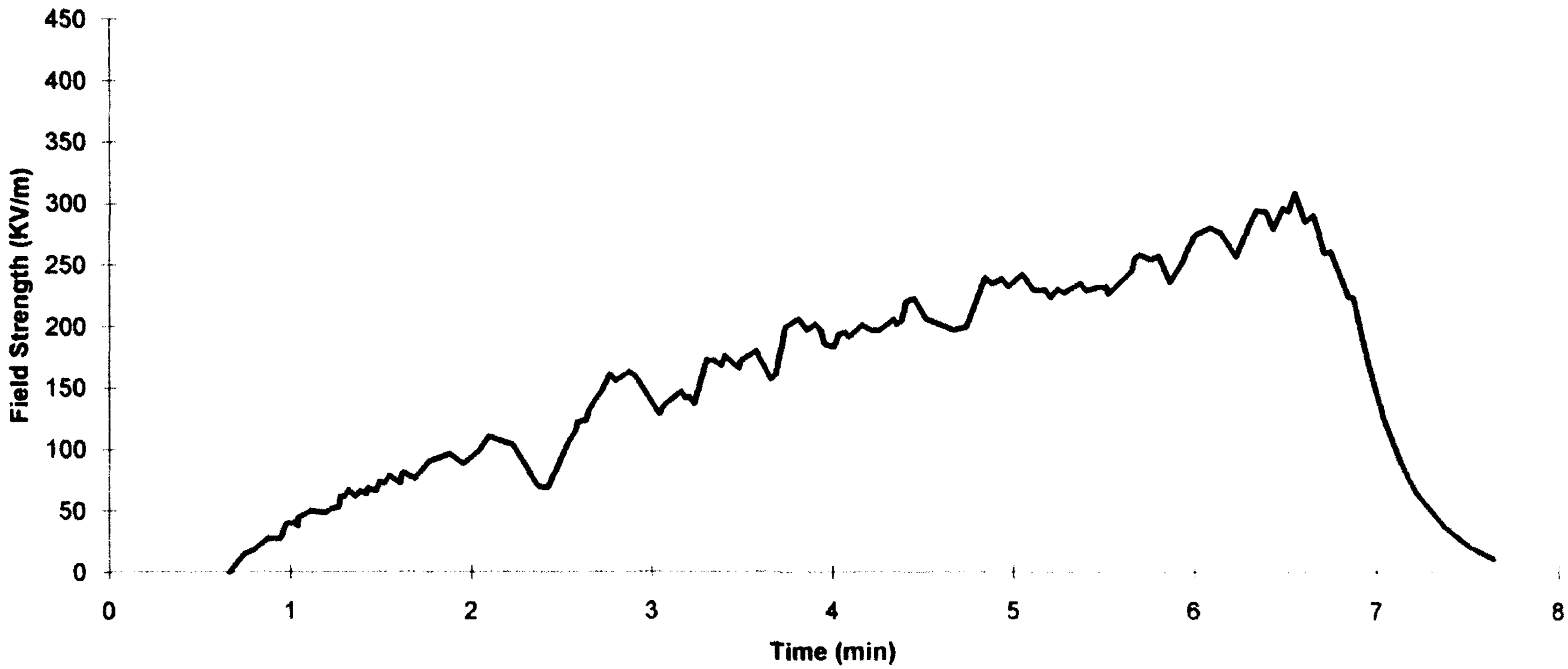


Figure 17--
Field Strength in Tank
RUN 19 -- Simulated Refueler & Tank Bonded & Grounded
Flow Rate =880 GPM   (Tires on Teflon)

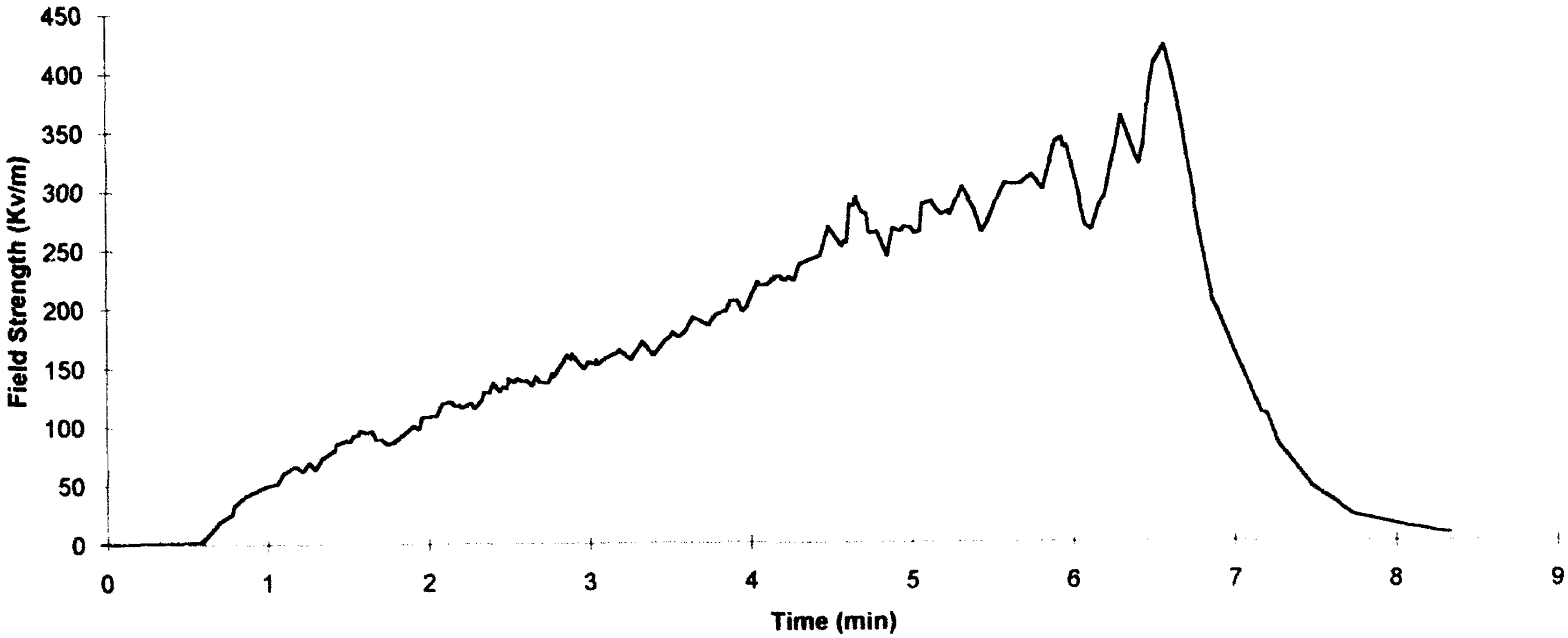


Figure 18--
Field Strength in Tank
RUN 22 -- Simulated Refueler & Tank Bonded & Grounded
Flow Rate =900 GPM (Tires on Teflon)

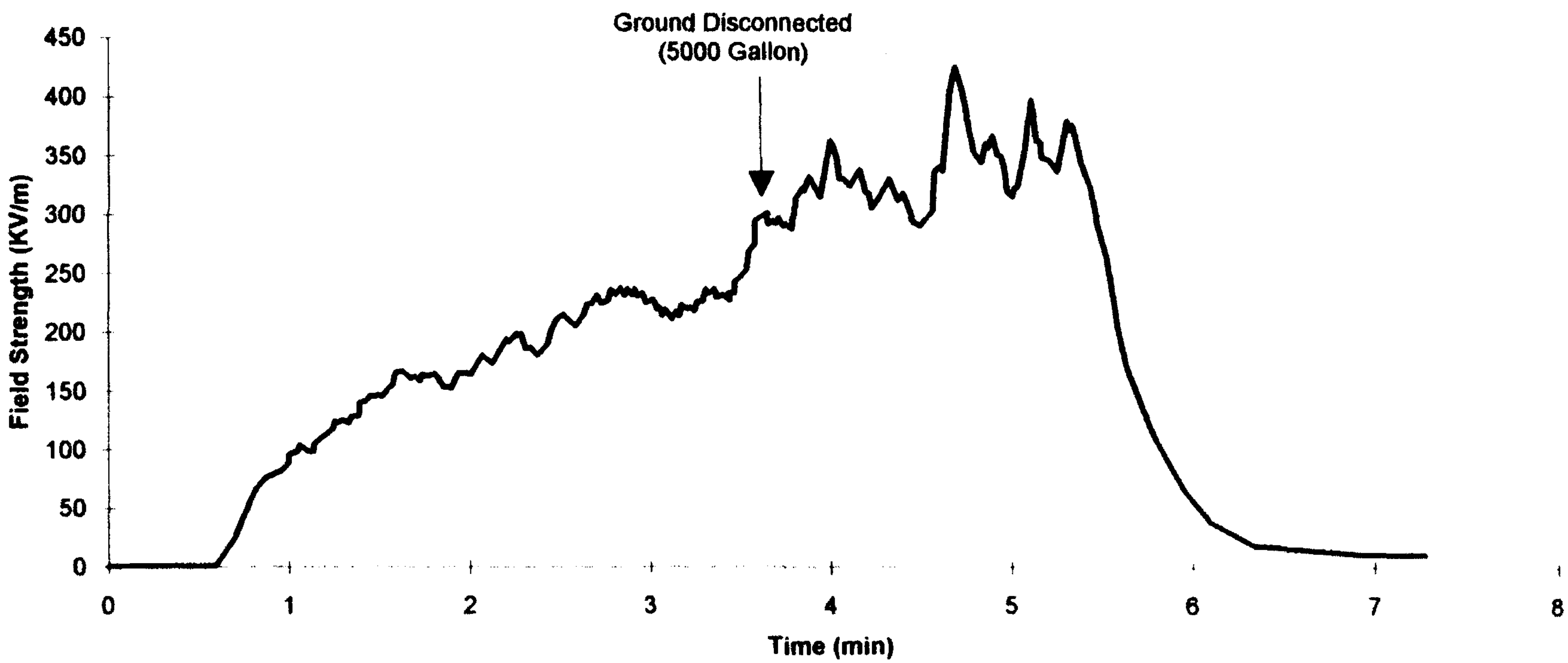


Figure 19--
Field Strength in Tank
RUN 23 -- Simulated Refueler & Tank Bonded NOT Grounded
Flow Rate =900 GPM (Tires on Teflon)

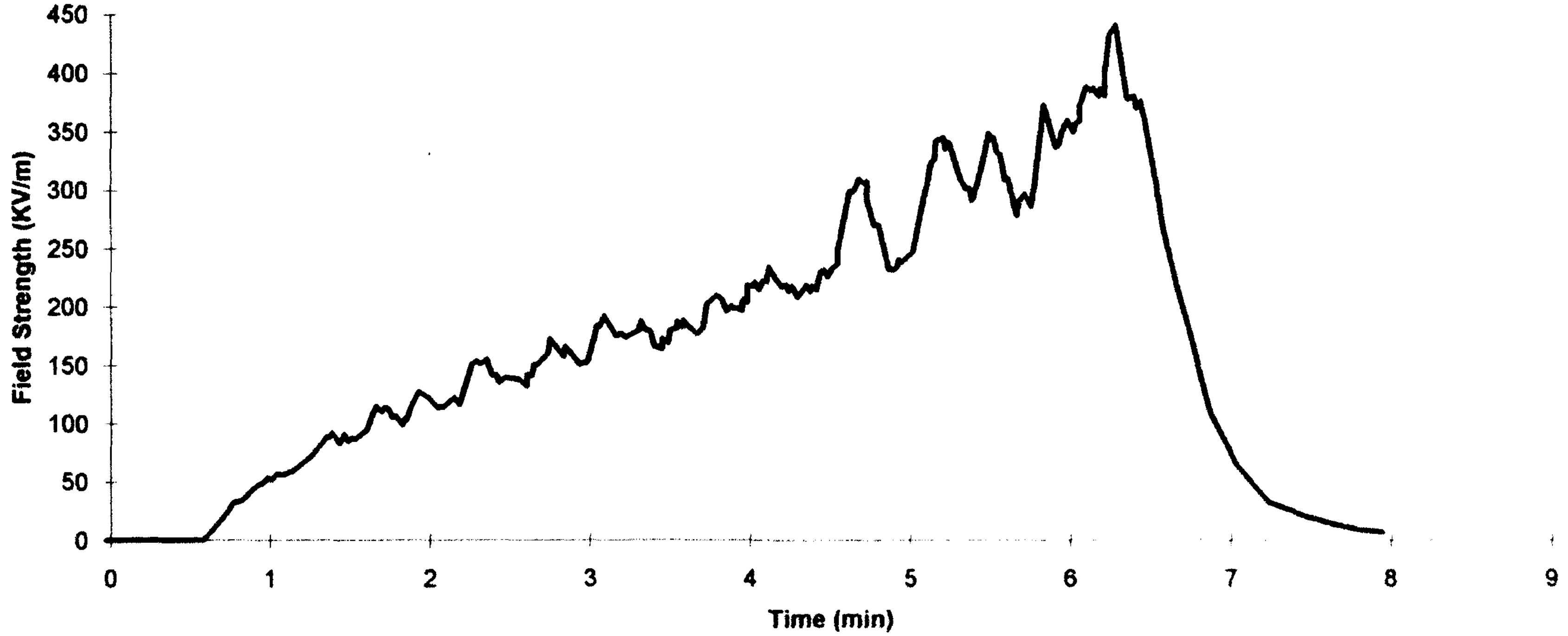
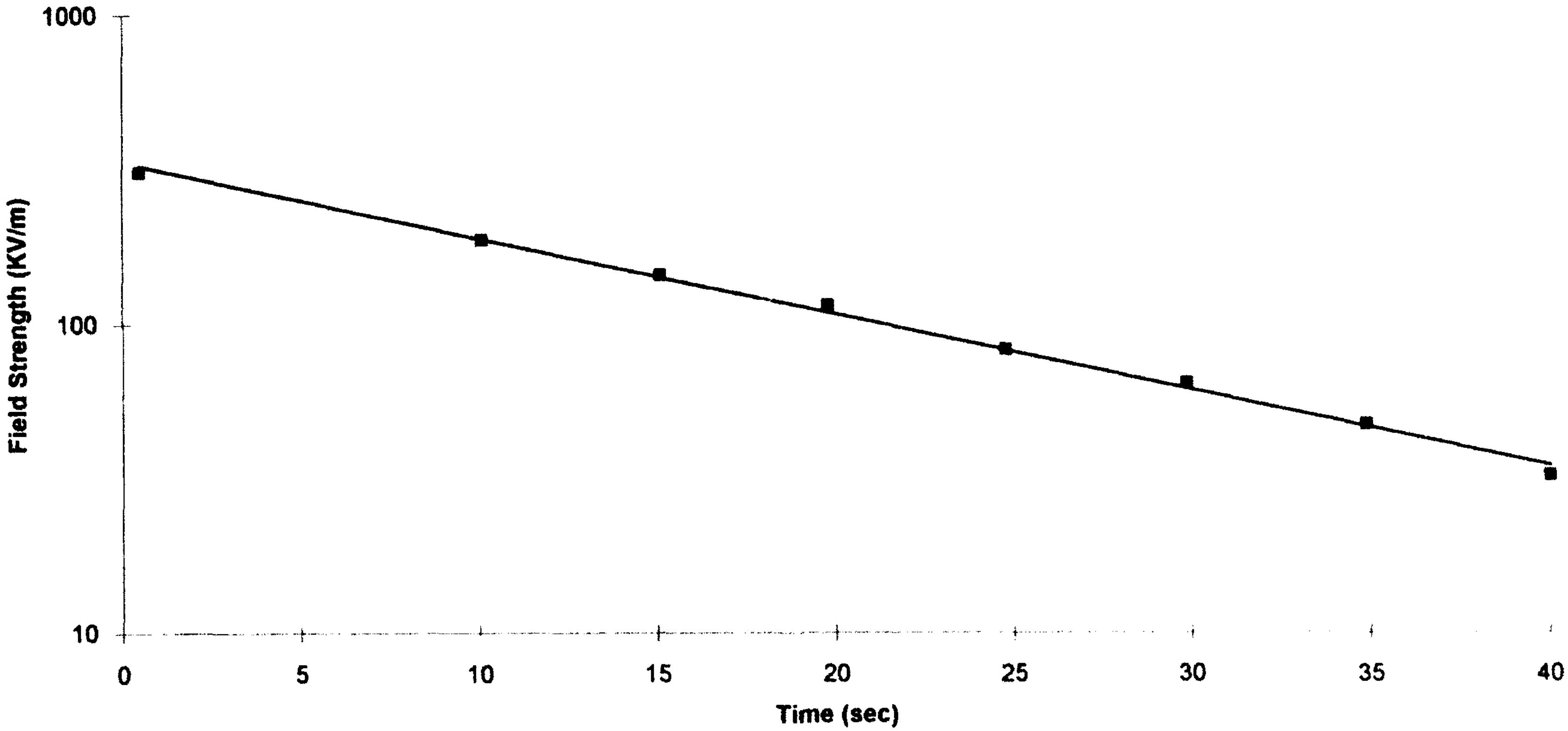


Figure 20--
Charge Decay Curve for Run 23



APPENDIX A

CRC BONDING AND GROUNDING TASK FORCE

APPENDIX A

CRC BONDING AND GROUNDING TASK FORCE

Name	Affiliation
J. T. Leonard, Leader*	Naval Research Laboratory
W. G. Dukek	Consulant
H. M. Gammon	Gammon Technical Products
E. S. Matulevicius*	EXXON R&E Co.
J. W. Muzatko*	Chevron Research Co.
F. O'Neill*	United Airlines
J. E. Schmidt	Boeing Commercial Airplane Co.
R. Wayman*	Federal Express

* Participant in Denver Test Program. In addition, J. B. Hoover and C. R. Fulper of the Naval Research Laboratory also participated in this program.